

AN INVESTIGATION INTO 88 KV SURGE ARRESTER FAILURES IN THE ESKOM EAST GRID TRACTION NETWORK



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Synopsis

The Eskom East Grid Traction Network (EGTN) supplying traction loads and distribution networks has experienced a high number of surge arrester failures over the past ten years. These failures result in poor network reliability and customer dissatisfactions which are often overlooked. This is because network reliability evaluation methodologies and reliability indices used in transmission business are different to those used in the distribution business. It is suspected that fast transient faults in this network initiate system faults leading to surge arrester design parameter exceedances and poor network insulation coordination.

Preliminary investigations into surge arrester failures in the EGTN suggest that transient studies were not done during network planning and design stages. This may have resulted in the lack of surge arrester parameter evaluations under transient conditions leading to improper surge arresters being selected and installed in this network resulting in surge arrester failures that are now evident. These failures may also have been exacerbated by the dynamic nature of traction loads as they are highly unbalanced, have poor power factors and emit high voltage distortions.

Poor in-service conditions such as defects, insulation partial discharges and overheating, bolted faults in the network and quality of supply emissions can also contribute to surge arrester failures.

To address problems arising with different reliability indices in these networks the reliability of the EGTN is evaluated. In this work the reliability evaluation of the EGTN is done by computing common distribution reliability indices using analytic and simulation methods. This is done by applying the analytic method in the EGTN by assessing network failure modes and effects analysis (FMEA) when the surge arrester fails in this network. The simulation method is applied by applying and modifying the MATLAB code proposed by Shavuka et al. [1]. These reliability indices are then compared with transmission reliability indices over the same period. This attempts to standardize reliability evaluations in these networks.

To assess the impact of transient faults in the surge arrester parameter evaluation the EGTN is modelled and simulated by initiating transient faults sequentially in the network at different nodes and under different loading conditions. This is done by using Power System Blockset (PSB), Power System Analysis Toolbox (PSAT) and Alternate Transient Program (ATP) simulation tools and computing important surge arrester parameters i.e. continuous operating voltage, rated voltage, discharge current and energy absorption capability (EAC). These parameters are then evaluated against parameters provided by manufacturers, the Eskom 88 kV surge arrester specification and those parameters recommended in IEC 60099-4.

To assess the impact and contribution of in-service conditions, faults and quality of supply emissions in surge arrester failures these contributing factors are investigated by assessing infra-red scans, fault analysis reports, results of the sampled faulted surge arrester in this network and quality of supply parameters around the time of failures.

This study found that Eskom transmission and distribution network reliability indices can be standardized as distribution reliability indices i.e. SAIDI, SAIFI, CAIDI, ASAI and ASUI indices are similar to Eskom transmission indices i.e. SM, NOI, circuit availability index and circuit unavailability index respectively. Transient simulations in this study showed that certain surge arresters in the EGTN had their rated surge arrester parameters exceeded under certain transient conditions and loading conditions. These surge arresters failed as their discharge currents and EACs were exceeded under heavy and light network loading conditions. This study concluded that surge arresters whose discharge currents and EACs exceeded were improperly evaluated and selected prior to their installations in the EGTN. This study found the EAC to be the most important parameter in surge arrester performance evaluations. The Eskom 88 kV surge arrester specification was found to be inadequate, inaccurate and ambiguous as a number of inconsistencies in the usage of IEEE and IEC classification systems terminology were found. It was concluded that these inconsistencies may have led to confusions and possibly incorrect calculations by manufacturers during surge arrester designs. Ultimately, this would have led to inadequate surge arresters being selected and installed by Eskom in the EGTN.

The evaluation of fault reports showed that two surge arrester failures in this network were caused by hardware failures such as conductor failure and poor network operating as the line was continuously closed onto a fault.

There was no evidence that poor in-service and quality of supply emissions contributed to surge arrester failures in this network.

PSB, PSAT and ATP simulation tools were found adequate in modelling and simulating the EGTN. However, the PSB tool was found to be slow as the network expanded and the PSAT required user defined surge arrester models requiring detailed manufacture data sheets which are not readily available. ATP was found to be superior in terms of speed and accuracy in comparison to the PSB and PSAT tools. The MATLAB code proposed by Shavuka et al. [1] was found to be suitable and accurate in assessing transmission networks as EGTN's reliability indices computed from this code were comparable to benchmarked Eskom distribution reliability indices.

The work carried out in this research will assist in improving surge arrester performance evaluations, the current surge arrester specification and surge arrester selections. Simulation tools utilized in this work show great potential in achieving this. Reliability studies conducted in this work will assist in standardizing reliability indices between Eskom's transmission and distribution divisions. In-service condition assessment carried out in this work will improve surge arrester condition monitoring and preventive maintenance practices.

Table of Contents

Table of Contents

Declaration	Error! Bookmark not defined.
Acknowledgements	i
Synopsis.....	ii
Table of Contents	iv
Acronyms and definitions.....	x
Surge arresters definitions used in this dissertation.....	xiii
Chapter 1. Introducing the research problem	- 1 -
1.1 Surge arrester failures in the EGTN and their impact on customers	- 1 -
1.2 Background to this research and description of the case study	- 1 -
1.2.1 Surge arrester performance evaluations and milestones.....	- 3 -
1.3 Research motivation	- 4 -
1.4 Research contributions	- 5 -
1.5 Research hypothesis	- 5 -
1.6 Research questions	- 5 -
1.7 Research scope and limitations.....	- 6 -
1.8 Dissertation outline.....	- 6 -
1.9 Conference papers presented during the course of this research	- 7 -
Chapter 2.	- 8 -
Power system design and impacts of voltage surges in insulation coordination	- 8 -
2.1 Introduction	- 8 -
2.2 Power system insulation coordination	- 8 -
2.2.1 Introduction	- 8 -
2.2.2 Basic impulse insulation level	- 9 -
2.2.3 Specification of the BIL	- 9 -
2.2.4 Switching impulse level.....	- 9 -

2.2.5	Power frequency withstand voltage.....	- 10 -
2.2.6	The role of surge arresters in power system's insulation coordination	- 10 -
2.3	Insulation coordination methods in power systems.....	- 10 -
2.3.1	Conventional method.....	- 11 -
2.3.2	Statistical method	- 11 -
2.4	Utilization of metal oxide surge arresters in insulation coordination.....	- 13 -
2.5	Power system surges.....	- 14 -
2.5.1	Modelling power system surges	- 14 -
2.6	Causes of overvoltages in power systems	- 16 -
2.6.1	Internal overvoltage causes	- 16 -
2.6.2	External causes of surges in power systems	- 17 -
Chapter 3.		- 18 -
Power systems reliability.....		- 18 -
3.1	Introduction	- 18 -
3.2	Power systems reliability evaluation methods.....	- 18 -
3.2.1	Analytical method.....	- 19 -
3.2.2	Simulation methods	- 19 -
3.3	Transmission and distribution performance evaluations	- 19 -
3.3.1	Introduction	- 19 -
3.3.2	Reliability evaluation of the Eskom transmission system	- 19 -
3.3.3	Reliability evaluation of Eskom's distribution system	- 22 -
3.3.4	Determination of unserved energy in utilities	- 24 -
Chapter 4.		- 26 -
Traction systems.....		- 26 -
4.1	Introduction	- 26 -
4.2	The structure and features of traction systems	- 26 -
4.3	Impacts of traction loads on the power system's quality of supply	- 27 -

4.3.1	Evaluation of voltage unbalances in power networks	- 27 -
4.3.2	Evaluation of current unbalances in power networks	- 28 -
4.3.3	Evaluation of current and voltage harmonics in traction systems	- 30 -
4.4	Evaluation of voltage regulation in traction systems.....	- 32 -
4.5	Traction load modelling.....	- 32 -
Chapter 5.		- 34 -
Design, operation, classification and selection of surge arresters		- 34 -
5.1	Introduction	- 34 -
5.2	Basic surge arrester design principles	- 34 -
5.3	Basic surge arrester operation principle	- 35 -
5.4	Surge arrester types, classification and general applications.....	- 36 -
5.5	Surge arrester classification and identification.....	- 37 -
5.6	Application of surge arresters.....	- 39 -
5.6.1	Different types of MOSAs and their applications	- 39 -
5.6.2	Wrapped design metal oxide surge arresters	- 40 -
5.7	Energy absorption capabilities of a surge arrester	- 40 -
5.7.1	Evaluation of surge arrester energy absorption withstand capabilities.....	- 41 -
5.7.2	Computation of energy absorption capabilities in surge arresters for selection purposes ...	- 43 -
5.8	In-service factors impacting surge arrester performance.....	- 47 -
5.8.1	Causes of in-service surge arrester deterioration.....	- 47 -
5.8.2	Modes of surge arrester failures	- 49 -
5.8.3	Shattering of the surge arrester housing	- 49 -
5.8.4	Internal flashovers	- 49 -
5.8.5	Overloading	- 49 -
Chapter 6.		- 50 -
Reliability evaluation of the EGTM.....		- 50 -
6.1	Introduction	- 50 -

6.2	Representation of the EGTN for reliability evaluation using the analytical method.....	50 -
6.3	Computation and comparison of the EGTN's reliability indices	51 -
6.3.1	Evaluation of Umfolozi 88 kV feeder 1 reliability indices.....	51 -
6.3.2	Evaluation of Umfolozi 88 kV feeder 2 reliability indices.....	52 -
6.3.3	Evaluation of Bloedrivier 88 kV feeder 1 reliability indices.....	53 -
6.4	Modelling and simulation of the EGTN in PSB, PSAT and ATP tools	55 -
6.5	Proposed model of the traction network in PSB tool	55 -
6.5.1	Application of the proposed PSB model in EGTN.....	55 -
6.5.2	Description of the EGTN model parameters and simulation method in PSB.....	56 -
6.6	EGTN modelling and simulation in PSAT	56 -
6.6.1	Description of the EGTN model parameters and simulation method in PSAT	56 -
6.7	EGTN modelling and simulation in ATP tool.....	57 -
6.7.1	Description of the EGTN model parameters and simulation method in ATP tool.....	58 -
Chapter 7		59 -
7.1	Presentation and discussion of PSB, PSAT and ATP simulation results	59 -
7.2	Steady state simulation results of the EGTN in PSB tool.....	59 -
7.2.1	EGTN 88 kV steady state busbar and surge arrester voltages at full load conditions	59 -
7.2.2	EGTN 88 kV steady state busbar and surge arrester voltages at 0.85pf	61 -
7.2.3	EGTN 88kV steady state busbar and surge arrester voltages at 0.7pf	63 -
7.3	Transient state simulation results of the EGTN model in PSB tool	66 -
7.3.1	Breaker states for a fault at Umfolozi at full loading, 1pf	66 -
7.3.2	Surge arrester voltage and current waveforms for a fault at Umfolozi at full loading	67 -
7.3.3	Breaker states for a fault at Bloedrivier at full loading.....	68 -
7.3.4	Breaker states for a fault at Normandie at full loading.....	70 -
7.3.5	Surge arrester voltage and current waveforms for a fault at Normandie at full loading.....	70 -
7.3.6	Breaker states for a fault at Empangeni at full loading.....	72 -
7.3.7	Surge arrester voltage and current waveforms for a fault at Empangeni at full loading	72 -

7.4	Summary of PSB simulation results under different contingencies	73 -
7.4.1	Simulation results for different faults in the EGTN under 0.85 pf loading conditions.....	73 -
7.4.2	Simulation results for different faults in the EGTN under 0.7 pf loading conditions.....	74 -
7.5	Performance evaluation of surge arresters in the EGTN model in PSB tool under different loading and fault conditions	75 -
7.5.1	Parameter evaluation of surge arresters in EGTN for different faults under full loading conditions	75 -
7.5.2	Parameter evaluation of surge arresters in EGTN for different faults under 0.85 pf loading conditions	75 -
7.5.3	Parameter evaluation of surge arresters in EGTN for different faults under 0.7 pf loading conditions	76 -
7.6	Comparison of surge arrester parameters computed from PSB, PSAT and ATP tools	77 -
7.6.1	Comparison of U_c and U_r parameters computed from PSAT and PSB tools.....	77 -
7.6.2	Comparison of U_c and U_r parameters computed from ATP and PSB tools.....	77 -
7.6.3	Comparison of I_d parameters computed from ATP and PSB tools.....	77 -
7.6.4	Comparison of EAC parameters computed from ATP and PSB tools	77 -
7.6.5	Comparison of U_c and U_r parameters computed from PSAT and ATP tools	78 -
Chapter 8.		79 -
Assessing contributing factors in surge arrester failures in the EGTN.....		79 -
8.1	Description of incidents.....	79 -
8.2	Evaluation of the EGTN surge arrester's infrared scans reports and metallurgy report.....	82 -
8.2.1	Analysis of surge arrester infrared scans	82 -
8.2.2	Analysis of metallurgy report for samples taken to the Eskom's testing centre.....	82 -
8.3	Evaluation of the Eskom 88 kV surge arrester specification.....	83 -
Chapter 9.		85 -
9.1	Conclusions and future work.....	85 -
9.2	Answers to research questions.....	85 -
9.3	Research hypothesis validation and research findings	87 -

9.4	Implications of the research findings.....	- 88 -
9.5	Concluding remarks and final thoughts.....	- 89 -
Chapter 10.	Bibliography	- 90 -
Appendix A		- 98 -
Appendix B.....		- 104 -
Appendix C.....		- 141 -
Appendix D		- 144 -

Acronyms and definitions

The following acronyms as they appear in this dissertation are commonly used in power systems studies.

Acronym	Description of the acronym
AC	Alternating Current
AENS	Average Energy Not Served
AME	Asset Management Execution
ARC	Auto Reclosing
ASAI	Average System Availability Index
ASUI	Average System Unavailability Index
ATP	Alternate Transient Program
BIL	Basic Insulation Level
BKR	Breaker
BSAEAC	Bloedrivier surge arrester energy absorption capability
BSAIE	Bloedrivier surge arrester instantaneous energy
CAIDI	Customer Average Interruption Duration Index
CAIFI	Customer Average Interruption Frequency Index
DC	Direct Current
DH	Distribution or line surge arrester with High duty
DL	Distribution or line surge arrester with Low duty
DM	Distribution or line surge arrester with Medium duty
EAC	Energy Absorption Capability
EF	Earth Fault
ENS	Energy Not Served
ESAEAC	Empangeni surge arrester energy absorption capability
ESAIE	Empangeni surge arrester instantaneous energy
FAT	Factory Acceptance Tests
HV	High Voltage
HVDC	High Voltage Direct Current
IEC	International Electricity Commission
IEEE	Institute of Electrical and Electronics Engineers
IRR	Internal Rate of Return
KZN	Kwa-Zulu Natal
LV	Low Voltage
MATLAB	Mathworks Laboratory
MCOV	Maximum Continuous Operating Voltage
MOSA	Metal Oxide Surge Arrester
MTS	Main Transmission Substation
MV	Medium Voltage
NERSA	National Energy Regulator of South Africa
NPV	Net Present Value
NSAEAC	Normandie surge arrester energy absorption capability

NSAIE	Normandie surge arrester instantaneous energy
P	Real power
pf	Power factor
PSAT	Power System Analysis Toolbox
pu	per unit
Q	Reactive power
RMS	Root Mean Square
SA	Surge Arrester
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Duration Index
SARB	South African Reserve Bank
SAUPEC	South African Universities Power Engineering Conference
SH	Station class surge arrester with high duty
SIPL	Switching Impulse Protection Level
SL	Station class surge arrester with Low duty
SM	Station class surge arrester with Medium duty
SM	System Minutes
SMt	Simulation Method
SPB	Power System Blockset
SSV	Steady State Voltage
TIPPS	Transmission Integrated Plant Performance System
TOVs	Temporal Over-Voltages
TSV	Transient State Voltage
USAEAC	Umfoloji surge arrester energy absorption capability
USAIE	Umfoloji surge arrester instantaneous energy

Symbols used

ω	Angular frequency
U_c	Continuous voltage
$^\circ$	Degrees
I_d	Discharge or impulse current through the arrester as it conducts
f	Frequency
kJ	kilo-Joules
km	kilometres
kV	kilo-Volts
λ	lambda
I	line current in the EGTN
U_m	Maxim system voltage
Q_{max}	Maximum VAR limit
V_{max}	Maximum Voltage limit

m	Meters
mm	millimetres
$Q_{\min}$	Minimum VAR limit
$V_{\min}$	Minimum Voltage limit
I_n	Nominal discharge current
U_n	Nominal system voltage
π	Pi
pf	Power factor
Q_{rs}	Repetitive charge transfer rating
U_{res}	Residual voltage
s	Seconds
c	Speed of light (3×10^8 km/second)
YNd1	Star to Neutral to delta connection with a 30 degree phase shift
U_r	Surge arrester's rated voltage
I_{ref}	Surge arrester's reference current
U_{ref}	Surge arrester's reference voltage
U_{ps}	Switching impulse protection level
U_s	System voltage
Q_{th}	Thermal charge transfer rating
W_{th}	Thermal energy rating
t	Time
T_1	Virtual front time of a current impulse
T_2	Virtual time to half-value on the tail of an impulse

Surge arrester definitions used in this dissertation

These terms are used in this dissertation and are defined in IEC 60099-4: 2014, edition 3 [2].

Terminology

Acceptance tests:

Description

Tests done by the manufacturer and accepted by the customer. These tests constitute an agreement between the two parties.

Continuous current of an arrester:

Current flowing through the arrester when energized at the continuous operating voltage.

Continuous operating voltage of an arrester:

Designated permissible RMS value of power-frequency voltage that may be applied continuously between the arrester terminals.

Designation of an impulse shape:

Combination of two numbers representing T_1 and T_2 . These are represented as a ratio of T_1/T_2 . This ratio distinguishes the steepness of both the wave front (T_1) and tail end (T_2) of the impulse voltage or current.

Discharge current of an arrester:

Impulse current which flows through the arrester as it clamps the voltage to ground during its conduction.

Distribution class arrester:

Arrester intended for use on distribution systems, typically of $U_s \leq 52$ kV, to protect components primarily from the effects of lightning.

Housing:

External insulating part of an arrester, which provides necessary creepage distance and protects the internal parts from the environment.

Impulse:

Unidirectional wave of voltage or current which, without appreciable oscillations, rises rapidly to a maximum value and falls, usually less rapidly, to zero with small, if any, excursions of opposite polarity, with defining parameters being polarity, peak value, front time and time to half - value on the tail.

Internal parts:

Metal oxide resistor with supporting structure and internal grading system, if equipped.

Lightning current impulse:

8/20 current impulse with limits on the adjustment of equipment such that the measured values are from $7\mu s$ to $9\mu s$ for the virtual front time and from $18\mu s$ to $22\mu s$ for the time to half-value on the tail.

Metal - oxide surge arrester without gaps:

Arrester having non-linear MO resistors connected in series and/or in parallel without any integrated series or parallel spark gaps, incorporated in a housing with terminals for electrical and mechanical connection.

Nominal discharge current of an arrester:

Peak value of lightning current impulse, which is used to classify an arrester.

Operating duty:

	The ability of the surge arrester to recover after injection of rated thermal energy under temporary overvoltage conditions.
Over-voltage condition:	A condition in the network where normal or operating voltages are exceeded for a short duration of time.
Power-frequency voltage versus time characteristic:	The maximum time durations for which corresponding power-frequency voltages may be applied to arresters without causing damage or thermal instability, under specified conditions in accordance with manufacture's supplied surge arrester data.
Rated voltage of an arrester:	Maximum permissible 10 seconds power frequency r.m.s. overvoltage that can be applied between the arrester, as verified by the Manufacturer in the TOV test and operating duty test.
Reference current of an arrester:	Peak value (the highest peak value of two polarities if the current asymmetrical) of the resistive component of a power-frequency current used to determine the reference voltage of the arrester.
Reference voltage of an arrester:	Peak value of power frequency voltage divided by $\sqrt{2}$, which is obtained when the reference current flows through the arrester.
Repetitive charge transfer rating:	Maximum specified charge transfer capability of an arrester, in the form of a single event or group of surges that may be transferred through an arrester without causing mechanical failure or unacceptable electrical degradation to metal oxide resistors.
Residual voltage of an arrester:	Peak value of voltage that appears between the terminals of an arrester during the passage of discharge current.
Routine tests:	Tests made on each arrester, or on parts and materials, as required, to ensure that the product meets the design specifications.
Steady state voltage:	Voltage measured at a particular point in the network at steady state condition.
Station class arrester	Arresters intended for use in stations to protect equipment from transient overvoltages, typically but not only intended for use on systems of $U_s \geq 72.5$ kV.
Switching impulse protection level (U_{ps})	The maximum residual of the arrester for the switching impulse discharge current specified for its class.

Transient state voltage:	Voltage measured at a particular point in the network at transient state condition.
Thermal energy rating:	Maximum specified energy, given in kJ/kV of U_r that may be injected into an arrester or arrester section within 3 minutes in a thermal recovery test without causing thermal runaway.
Thermal runaway of an arrester:	Situation when the sustained power loss of an arrester exceeds the thermal dissipation capability of the housing and connections, leading to a cumulative increase in temperature of the MO resistor elements culminating in failure.
Thermal stability of an arrester:	State of an arrester if, after an operating duty causing temperature rise, the temperature of the MO resistor elements decreases with time when the arrester is energised at specified continuous operating voltage and at specified ambient conditions.
Type tests:	Tests which are made upon the completion of the development of a new arrester design to establish representative performance and to demonstrate compliance with the relevant standard.
Virtual duration of the peak of a rectangular impulse:	Time during which the amplitude of the impulse is greater than 90% of its peak value.
Virtual front time of a current impulse:	Time in microseconds equal to 1.25 multiplied by the time in microseconds for current to increase from 10% to 90% of its peak value.
Virtual time to half-value on the tail of an impulse:	Time interval between the virtual origin and the instant when the voltage or current has decreased to half its peak value, expressed in microseconds.

Chapter 1. Introducing the research problem

In this chapter the research problem is introduced, surge arrester failures in traction networks and their adverse impact on the reliability of the network are discussed. The background in surge arrester failures in the EGTN is given. Limitations and inaccuracies in the selection of surge arresters during network planning and design stages are identified leading to the formulation of the research hypothesis.

1.1 Surge arrester failures in the EGTN and their impact on customers

Eskom East Grid transmission has experienced a high number of surge arrester failures over the past ten years. These failures seem to adversely impact the reliability of this network and has caused customer dissatisfaction. Preliminary investigations suggest that these failures may be due to the lack of surge arrester performance evaluations during network planning and design stages. It appears this led to the poor selection of surge arresters and network insulation coordination resulting in surge arrester failures over time. Differences in reliability evaluation approaches and different reliability indices between transmission and distribution businesses suggests that the impact of these failures to distribution customers is far greater than currently quantified by transmission.

The objectives of this research are firstly to investigate if surge arrester parameters can be evaluated prior to the selection of surge arresters using the EGTN as the case study. In order to carry out this work PSB, PSAT and ATP tools are utilized to compute surge arrester parameters in the EGTN and compare them with surge arrester parameters provided by manufacturers and the Eskom surge arrester specification. Secondly, to assess if the reliability evaluations approaches between distribution and transmission can be standardized such that any adversely impacts experienced by transmission customers are readily known. In order to do this, common reliability indices are computed by using the analytical and simulation methods. In order to increase the speed of computation of these reliability indices the simulation method is also improved by applying the MATLAB code proposed by Shavuka et al. These reliability indices are then used to assess the overall network. Finally, other in-service conditions are assessed to investigate if there are any other factors that may have contributed to these failures. This is done by assessing infra-red scans, analyzing fault reports and quality of supply reports.

1.2 Background to this research and description of the case study

The East Grid is part of the Eskom transmission grid that supplies various major industrial, commercial customers and distribution loads in KwaZulu Natal regions. The EGTN is made up of Umfolozi, Bloedrivier, Normandie and Empangeni substations. These substations are equipped with 2x160 MVA three phase transformers that step down 275 and 400 kV voltages to 88 kV levels. In this network, traction loads are powered via dual phase 88/25 kV transformers as shown in Figure 1.1. EGTN's main substations are designed in compliance with N-1 contingency requirements in the transmission grid planning guide [3] and NRS 048 power quality requirements [4] and meeting transmission technical performance standards [5].

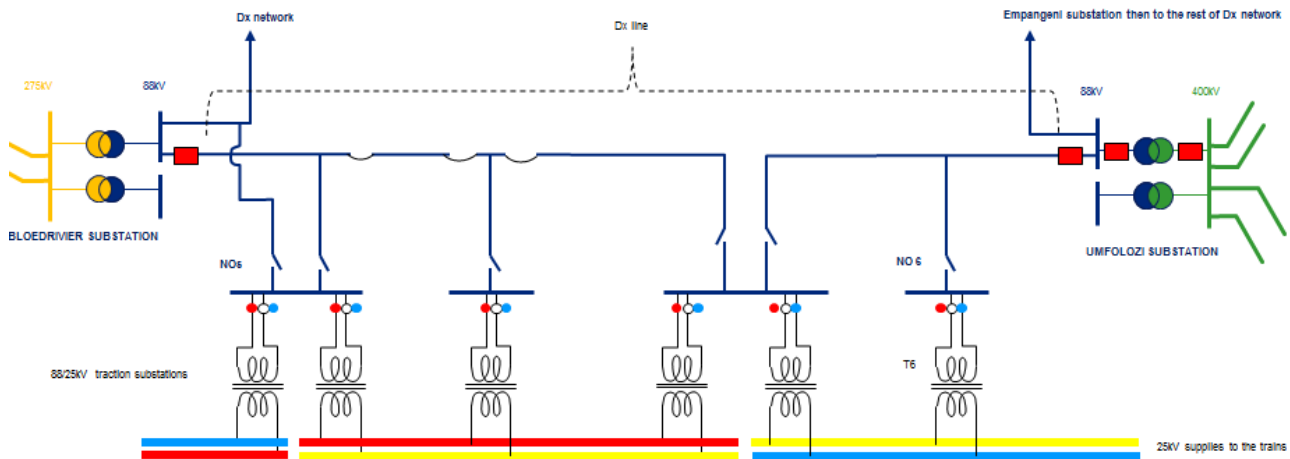


Figure 1.1: The network layout of the East Grid traction network

In avoiding the coupling of traction and distribution loads “clean” loads (loads free of voltage and current harmonics) and “dirty” loads (loads with high current and voltage harmonics), they are split at each transmission substation namely Umfolozi and Bloedrivier substations as indicated in Figure 1.1. This is done by linking each transformer to its own busbar to manage voltage unbalance limits and to prevent the over-utilization of on load tap changers (OLTCs). In order to speedily isolate faulty networks and improve this network’s reliability, normally opened (NO) points are utilized and the loading of the 88 kV line is balanced by alternating the supply to the train substations between phases as shown in Figure 1.1.

Traction systems are vital component of the transportation system that drives economic development in emerging economies [6] such as South Africa. In South Africa the power grid and traction systems are owned and operated by Eskom and Transnet respectively with the sole purpose of transporting goods and materials. These integrated systems are becoming more complex due to network expansion, power flow state changes brought about deviations and uncertainty in system responses to technological advancements [7]. The expansion and inter-connectivity of the power system poses security of supply problems due to faults such as lightning strikes, fires, hardware failures and bird related faults [8]. The occurrence of interruptions of supply inhibits the utility’s ability to source funding and adjust tariffs. Interruptions also lead to high cost of unserved energy and general customer dissatisfaction. The appraisal of the transmission network is thus critical and is done by assessing both severe and non-severe system minutes (SMs). Severe SMs are due to interruptions that have durations greater than 1 SM, whilst non-severe SMs are due to interruptions with durations of less than 1 SM [5].

The presence of faults including the failure of auxiliary equipment such as surge arresters usually leads to interruptions of supplies. Surge arrester failures are detrimental to the reliability of the power grid and the networks that it supplies as evident in the EGTN where these failures lead to poor system performance. This is because surge arresters protect 88 kV power lines which are a backbone to the security of supply of traction loads and other loads. For instance, 11 and 22 kV loads are also fed from the EGTN thus surge arrester failures often lead to interruptions of supplies and/or prolonged network re-configurations during fault investigations.

Over the past ten years, the East Grid has experienced a high number of interruptions of supplies in the EGTN which resulted in poor network performance, reputational damage, loss of revenue and risk of damage to nearby equipment. Several investigations including the investigation carried by [9] showed that some surge arresters in this network were deficient and/or insufficient in some way that is not clear. This led to the conclusion that the problem of interruptions cannot be solved effectively without a greater understanding of the behavior of the traction network. This is because some solutions created new problems as stated in the findings and recommendations in [9].

In particular, the suggestion of installing 132 kV surge arresters in 88 kV systems is quite problematic as it seems to defeat the very purpose of the surge arrester. The implementation of this recommendation would

effectively expose other equipment (such as transformers) to overvoltages and may lead to Eskom incurring further replacement costs. It is thus necessary to understand parameters that are important in the performance evaluation of a surge arrester and how the power grid and traction network should be modelled and simulated for the computation of these parameters. *Inter alia* it is important to understand how the performance of a surge arrester can be evaluated against parameters provided by manufacturers and those parameters specified by the utility to assess the surge arrester selection process. This may form part of critical steps in the development of design inputs in the surge arrester selection process for new surge arrester installations and replacement projects.

1.2.1 Surge arrester performance evaluations and milestones

The performance evaluation of surge arresters involves the computation and evaluation of their parameters for surge arrester selections in new and existing installations. The main objectives of surge arrester performance evaluation are to ensure that:

- The surge arrester can withstand stresses caused by foreseen and expected events in the network such as faults.
- Surge arrester models are adequate and accurate for the computation of surge arrester parameters and their evaluations.
- Surge arrester parameters remain within desirable limits after contingencies such as faults and loading conditions [10], [11].
- The power system reliability is not compromised and that critical components are protected against dangerous voltages [12].

The understanding of the power system behavior or its characteristic is derived from its simulation results i.e. the solution to its load flow problem such as the behavior of bus voltages, angles and current flows under certain events or contingencies [13]. Open source tools are commonly utilized to generalize the behavior of a particular system because they are easily accessible as they are usually not licensed and/or have limited stringent license conditions [7], [14]. Power System Blockset (PSB), Power System Toolbox (PST) and Power System Analysis Toolbox (PSAT) are commonly used open source tools in power system simulation and analysis. These tools are run in MATLAB simulation platform that most researchers are familiar with and allow the user to input physical properties of the system and simulate its responses to certain events. This assists in the quick simulation to have a general understanding and characterization of a particular network hence these tools are popular. PST and PSAT tools are similar and have user defined functions and broad libraries of test files that can be modified depending on the network elements to be simulated [7]. Alternate Transient Program (ATP) is a licensed simulation tool commonly used in industry for fast transient simulations and its simulation speed is faster than those of PSB and PSAT [14].

It is for these reasons that in this study PSB, PSAT and ATP tools are used to model and simulate the EGTN in order to compute important surge arrester parameters. The results obtained using these tools are validated and compared and utilized in the assessment of surge arrester performance and selection. The assessment of suitability in this study is done by comparing surge arrester parameters computed from each tool against surge arrester datasheets provided by suppliers of surge arresters that are installed in EGTN. The simulation methodology and the accuracy of the simulation depend on how elements of interest are modelled and represented in the overall power system analysis. There are various surge arrester models that exist for surge arrester performance evaluations such as IEEE, Pinceti-Giannettoni, fast time and frequency domains and the recent finite element analysis [15]. However, these models do not take into account the impact of the overall power system performance on surge arresters. This is because in these models surge arresters are treated as isolated devices connected to a constant voltage source. Thus, surge arrester parameters are analyzed without taking into account the behavior of the power grid.

Therefore, other important external events which have an impact on the performance of surge arresters in the network are not considered in these models. These events include transient faults such as breaker switching operations i.e. momentary opening and closing of breakers and their adverse effects on the performance of surge arresters. Compounding this problem are inconsistencies and ambiguities in power system operating voltage classifications and IEC and IEEE terminologies. Voltages are classified in terms of IEC and IEEE

system voltages [11] for equipment specification, simulations and/or testing and calculations. Thus, these inconsistencies and ambiguities could lead to incorrect simulation results and interpretation leading to poor choices in the selection of surge arresters such as Europe classify their networks using the IEEE standard. Surge arresters in the EGTN were/are manufactured abroad thus these differences may lead to different understanding and computation of surge arrester parameters.

Important surge arrester parameters in the evaluation of surge arrester performance are continuous operating voltages, rated voltage, rated discharge current, lightning impulse level and energy absorption or absorption capability, EAC [10]. Continuous operating voltage (U_c) is used for IEC classified system voltages but has a similar meaning to the maximum continuous operating voltage (MCOV) used in IEEE classified systems [11] in that these parameters both describe the voltage across arrester terminals however, they are computed differently. Similarly, the rated voltage (the voltage at which the surge arrester starts to clamp the voltage to ground) is dependent on the system operating voltage. Compounding this problem is the dependency of the rated voltage on the continuous operating voltage or MCOV, earthing arrangement considerations and voltage limits that have to be taken into account in the calculation of these parameters.

The energy absorption capability, EAC is the ability of the arrester to withstand or absorb energy during its conduction under fault conditions. This is the maximum energy that the surge arrester can absorb under a specific contingency without it failing. This parameter depends on the surge arrester's capability to absorb heat generated in arrester's resistors during its conduction and the type of material used in the arrester's housing. The evaluation of the arrester's EAC also depends on its MCOV or continuous operating voltage parameters. This makes the EAC the single most important surge arrester parameter in the evaluation of surge arrester performance. Thus, the above noted inconsistencies may lead to inaccuracies in the performance evaluation by manufacturers and poor selection decisions by the utility.

1.3 Research motivation

The failure of some components of a power system undermines its insulation coordination and reliability. The deficiencies in the coordination of the insulation expose system components to dangerous voltages which may compromise its reliability. The reliability of a power system is evaluated by accurately computing its reliability indices thus reliability tools used in these evaluations are important for operational and planning decisions [16], [17]. Analytical and simulation methods are used in power system reliability assessments where the former allows the system to be represented in the format that makes the understanding of failure modes and effects easier. However, network expansion makes these representations of the system cumbersome and time consuming thus the latter is preferred.

This realization has resulted in many simulation codes such as the proposed simulation code by Shavuka et al. [1]. Monte Carlo simulations are carried out using these codes to compute common reliability indices for reliability assessments. Shavuka et al. [1] applied this method in the Eskom Phillippi 22 kV network but this simulation code has not been applied in 88 kV networks. In this research this simulation code is adopted, modified and used to compute reliability indices of the EGTN and results are validated by comparing these indices with those computed from the analytical method i.e. failure modes and effects analysis (FMEA). This will also assist in the standardization of reliability assessments in transmission and distribution networks.

The uncertainty in the behavior of traction loads requires a simulation based approach to understand traction network characteristics. Simulation results from the power flow solution provide an effective and accurate diagnosis of network conditions that may result in identifying causes of surge arrester failures in networks feeding traction loads. This will ensure a full understanding of the traction network behavior and its impacts on the performance of surge arresters which can be used as design and planning inputs. Surge arresters are installed to protect the power system from dangerous overvoltages by conducting these voltages to ground [12]. The failure of these devices causes line trips that compromise the transmission network N-1 compliance, results in network unavailability and pose serious threats to the security of the entire power system [18] as observed in the EGTN.

Although there are some incidents that can be correlated to specific distribution line hardware failures, surge arrester failure causes in this network have not been established. This is compounded by the general lack of

understanding of traction operations by Eskom. This is because traction characteristics and their impact on the transmission grid have not been assessed. The characterization of traction networks by modelling and simulating the power grid and traction network is required. This requires overvoltage conditions such as faults to be simulated by initiating faults at certain points in the networks (busbars) and evaluating surge arrester performance under these different fault conditions. This will assist in the accurate selection of surge arresters during replacements and new installations in sections of the power grid that supply traction loads.

1.4 Research contributions

The review of the literature in this research will advance surge arrester performance studies and selections. The computation of reliability indices of the EGTN using MATLAB code proposed by Shavuka et al. [1] provides the East Grid with additional reliability assessment tools. The comparison of reliability indices done in this study enables a uniform method for reliability assessments for transmission and distribution business divisions. The modelling of the EGTN and simulation results from this study will enable the characterization of traction networks for all transmission grids. Simulation studies carried out in this research will also improve surge arrester selections for new installations particularly in networks supplying traction loads. The comparison of simulation tools and limitations noted in each of these tools in this study will assist other researchers in the selection of appropriate tools for surge arrester performance evaluations. The assessment of quality of supply parameters and in-service conditions carried out in this research will improve surge arrester condition monitoring methods and influence utilities maintenance practices.

1.5 Research hypothesis

The reliability of a power system must meet customer expectations, service level agreements, performance targets and set limits by the licensor. Simulation methodologies in reliability assessments are useful and attractive due their accuracy and high speed of computation. These methods promise to diversify simulation methodologies for transmission system's reliability evaluations and must be tested and validated. The current approach in surge arrester evaluation and selection methodology is based on the initial power system design and planning inputs where a surge arrester is merely modelled and assessed as a device connected to a constant power source. This approach may be insufficient for surge arresters installed in the power grid that supplies traction networks as these networks are inherently dynamic and cause voltage unbalances and distortions [19], [20], [21]. The presence of transient faults elsewhere in the network may result in more strain on surge arresters installed in networks feeding traction loads [7]. The changes in pre-fault and post fault conditions may alter surge arrester voltage-current characteristics compromising the overall power system insulation coordination. This requires a new approach in the modelling of the power grid and traction networks for the optimal surge arrester parameter performance evaluations and selection purposes.

The hypothesis of this research can therefore be worded as follows:

“Fast transients on traction systems initiate system faults that can be reduced by suitable insulation coordination through transient analysis to improve surge arrester performance evaluations, selections and improved system reliability at acceptable cost”.

It is possible to apply the MATLAB simulation code proposed by Shavuka et al. [1] and simulations of the EGTN to achieve this.

1.6 Research questions

The following research questions are posed to test the validity of this hypothesis:

- I. What is the process by which fast transients cause faults? How can the EGTN be modelled, simulated and analyzed to evaluate the impact of these transients on surge arrester performances?
- II. What methods can be used to evaluate the reliability of the network and what tools can be used to achieve this?
- III. How can these results be used to improve surge arrester selections?

- IV. Does the application of reliability evaluation methods and improved surge arrester selections lead to improved insulation coordination of this network?
- V. Will improved surge arrester selections and insulation coordination increase costs and is the benefit worth the extra cost?

1.7 Research scope and limitations

This research has the following limitations:

In order to simplify simulation results and avoid ambiguities any 88 kV mention that appears in this dissertation should be taken as a Root Mean Square (RMS) voltage. The modelling of faults in PSAT and ATP tools is done such that the fault occurs at 1.0 second and its duration at specific point in the network is 0.04 seconds i.e. a fault at 1 second is cleared after 1.04 seconds. It is assumed that the closing of the breaker occurs when the current is at a zero crossing. The sinusoidal voltage peak occurs instantaneously at the point when the fault is applied whilst the minimum occurs instantaneously when the fault is cleared i.e. no time delays due to slow closing/opening of breaker contact are taken into account. In this study a feeder failure rate of 0.065 failures/year-km and transformer restoration time of 200 hours are used in the reliability evaluation of the EGTN. It is also assumed that no repair work is undertaken during adverse weather conditions. Where normally opened points exist (such as Bloedrivier and Empangeni 88 kV lines) the time allowed for the closing of fuses or links to restore supplies to customers on the backbone is one hour and 5 hours for customers on the lateral. These are average restoration times for past failures in this network and they take into account the terrain of the area for fault finding and the distance from Eskom depots.

1.8 Dissertation outline

Chapter 1 introduces the research problem, evaluation of surge arresters for traction network applications and the reliability assessment of these systems. The work presented here includes a background to surge arrester selection and simulation practices at design and planning stages. Inaccuracies and inadequacies in these stages and factors leading to incorrect surge arrester selections are identified to formulate the research hypothesis.

Chapter 2 discusses elements of the power system design and the role of insulation coordination. Surge arrester designs, parameters and operating principles are discussed. The role of surge arresters in protecting the power system against voltage surges is also discussed.

Chapter 3 discusses reliability indices that are computed in the evaluation of reliability in power networks and current methodologies used in evaluating the reliability of transmission and distribution networks.

Chapter 4 deals with the characterization of traction network behavior and technical considerations that need to be made in the selection of surge arresters in these networks.

Chapter 5 gives a comprehensive theory of types of surges that adversely impact power systems and their causes. The behavior of surges or transients in power networks and their impact on surge arrester performance is discussed.

Chapter 6 discusses reliability approaches used in Eskom in the evaluation of transmission and distribution networks. The evaluation of the EGTN using analytical and simulation methods is also done in this chapter.

Chapter 7 discusses different modelling methodologies used in surge arrester performance evaluations. Models in PB, PSAT and ATP tools are also proposed and adopted for the simulation of the EGTN. Simulation results of the EGTN under different contingencies are also presented and discussed.

Chapter 8 discusses in service conditions during surge arrester failures in the EGTN. The findings of the laboratory report, review of quality of supply emissions and the review of the Eskom 88 kV surge arrester specification are also provided.

Chapter 9 provides answers to research questions that were posed in chapter 1 in order to validate the hypothesis. The scope and future work in surge arrester evaluation and performance studies is also detailed. The financial evaluation is also provided if Eskom adopts the recommendation to replace surge arresters in the

EGTN. Conclusions and recommendations based on simulation results in this study and condition monitoring factors are also made and a guide for selecting or replacing surge arresters in traction networks is proposed. Finally, the author's concluding remarks and final thoughts.

Chapter 10 gives a list of bibliography used in literature review. Appendices that contain useful information such as additional figures and tables that are also shown in this chapter.

1.9 Conference papers presented during the course of this research

These papers were presented at conferences in the course of this study:

- M. Mzulwini and K. Awodele, *An investigation into 88 kV Surge Arrester failures in Kwa-Zulu Natal Traction System*, South African Universities Power Engineering Conference (SAUPEC), South Africa, Johannesburg, 2016.
- M. Mzulwini and K. Awodele, *An impact of Fast Transient faults on Surge Arrester performance in Traction Networks*, South African Universities Power Engineering Conference (SAUPEC), South Africa, Stellenbosch, 2017.
- M. Mzulwini and K. Awodele, *Application of PSB, PSAT and ATP simulation tools in Traction Surge Arrester Selections*, South African Universities Power Engineering Conference (SAUPEC), Robotics and Mechatronics (RobMech), Passenger Rail Agency of South Africa (PRASA), South Africa, Bloemfontein, 2019.

Chapter 2.

Power system design and impacts of voltage surges in insulation coordination

In this chapter, important parameters in power system design and insulation coordination are discussed. The critical role played by surge arresters in optimal power system insulation coordination and safeguarding of customer loads is also highlighted.

2.1 Introduction

Power systems consist of transformers, insulators, surge arresters, connection clamps, etc. which are subjected to overvoltages. Overvoltages have adverse effects on the performance of protective devices as a few surges can cause harm to the power system's insulation. The interconnectivity of the power system results in significant voltage deviations which may overstress surge arresters [12].

A single failure of one component may result in other cascading failures with serious consequences on the power system management. These may cause loss of supply to customers, penalties incurred by utility, poor network performance, high cost of replacement, loss of revenue and the utility's reputational damage [16]. To understand causes of surge arrester failures, it is vital to understand the nature of the load supplied. It is also critical to assess the impact that voltage surges have on the overall power system, in this case, the EGTN.

Power systems must be designed and operated to withstand electrical insulation stresses and operating conditions. Surge arrester's design, selection and application must consider the changes in external environmental conditions such as pollution and animal interaction, particularly birds [8]. Hardware failures, parting of conductors, insulator failures due to corroded pins, switching surges, direct and indirect lightning strikes must also be considered in the selection and application of surge arresters in the network [22], [12]. Traction load current and voltage harmonics, voltage flicker, voltage unbalances, voltage dips, resonance and network switching procedures must also be considered. The analysis and assessment of these parameters ensures optimal power system coordination [23], [24], [19]. When this coordination is compromised, surge arrester failures might occur and can have detrimental effects and far-reaching consequences [25]. Despite this threat, surge arresters are often overlooked in the planning, design, and operation of power systems.

2.2 Power system insulation coordination

2.2.1 Introduction

Insulation technology is driven by the need for primary plant equipment to meet its insulation design limits. Complexities arise when the overall system insulation must be coordinated. This requires engineers to ask the following questions: *(i)* what insulation is required for a particular component and under what conditions? *(ii)* what are the properties of the material that make up that insulation? *(iii)* how does this insulation behave under voltage and current stresses? *(iv)* how should threats that may lead to component failures be mitigated or eliminated?

Insulation level is the withstand capability of a device to withstand voltage surges due to switching, lightning, hardware failures [12], [3], [26]. Generally, insulating components are designed to withstand breakdown voltage of 3 kV/mm at room temperature [22]. For example, an 11 kV glass disc insulator may flashover at 15 kV/mm or 18 kV/mm depending on its creepage distance [22]. Studying equipment insulation materials, basic insulation level (BIL), switching insulation level (SIL) and power frequency withstand voltages allows a better understanding of power system insulation and its coordination [3].

Power system insulation coordination is the optimal configuration of various protective devices such as current and voltage transformers, surge arresters, breakers and line traps [22]. Surge arresters play an important role in the protection of the equipment such as transformers, cables, and transmission lines against overvoltages [25].

2.2.2 Basic impulse insulation level

Basic insulation level (BIL) is the ability of an equipment's insulation system to withstand impulse voltages or surge voltages [3]. Therefore, surge arresters' insulation levels are designed to withstand temporary surge voltages, rather than only normal operating voltages. BIL increases with the power system's maximum and nominal voltages. Earthing configurations such as effectively grounded (resistive and inductive reactance values less than 3 Ω) or non-effectively grounded systems (resistive and inductive reactance greater than 3 Ω) are important in BIL specifications.

In Eskom, 66 kV system voltages and below are non-effectively grounded whilst 220 kV system voltages and above are effectively earthed [3]. It must be noted that the power system's BIL is much higher than the system maximum voltage (U_m) and nominal voltage (U_n) as shown in Table 2.1. This means that the power system protective devices must operate below their BIL.

Table 2.1: BIL, SWIL, U_m , U_n values for non-effectively earthed systems [3]

SYSTEM VOLTAGE KVRMS		IMPULSE WITHSTANDING VOLTAGE AT SEA LEVEL KV PEAK		SIXTY SECOND POWER FREQUENCY WITHSTAND VOLTAGE AT SEA LEVEL
(U_m) HIGHEST	(U_n) NOMINAL	BIL	SWIL	KVRMS
12 24	11 22	95 150		28 50
36 48 72 100 145 245	33 44 66 88 132 220	200 250 350 380 (450) 550 (650) 825		70 95 140 150 (185) 230 (275) 360
300 362 420	275 330 400	1050 1300 1425	850 950 1050	460 570 630
800	765		1550	-

2.2.3 Specification of the BIL

The specification of the BIL is based on how rapid the test waveform i.e., how well we can simulate a lightning impulse depending on how far we are from the sea. Eskom's equipment BIL is selected based on the lightning impulses that can be limited by surge arresters. This allows about a 20% margin for voltage drop in the leads between the arrester and the equipment to be protected [3], [26]. It should be noted that there is no discernable formulae for specifying the BIL. The specification of the BIL is thus based on minimum insulation level that all equipment can withstand. It is good engineering practice to specify the BIL inclusive of both internal and external insulation to allow for a greater safety margin. This ensures that when flashovers occur, they will occur over the external insulation [12]. For example, 88 kV surge arresters have a BIL of 380 kV (as specified in Table 2.1) which is above operating limits. Thus, 88 kV surge arresters in the EGTN are not likely to fail due to this parameter.

2.2.4 Switching impulse level

Switching impulse levels (SILs) are impulses arising from network switching a part or section of the power system. These impulses have longer durations than lightning impulses [3] and are directly proportional to the system maximum voltage. They are generally expressed as:

$$SIL = 2.5 K \frac{\sqrt{2}}{\sqrt{3}} U_m \quad \dots\dots\dots (2.1)$$

Where K is the withstand to breakdown factor ($1 \leq K \leq 1.15$) and U_m is the system maximum voltage. SIL values are usually given as network impedances where a large SIL value represents a highly capacitive network and a lower SIL value indicates an inductive or resistive load [27]. SIL increases in long lossless lines feeding capacitive loads due to higher capacitances [28]. This is because capacitive loads can lead to induced overvoltages which may exceed the surge arrester design limits. In practice, SIL values are rarely used as they are extremely hard to calculate. This is because the power network is interconnected with many short, medium,

and long line sections. This makes SIL an inaccurate parameter for surge arrester performance evaluations and selections in the EGTN.

2.2.5 Power frequency withstand voltage

Power frequency withstand voltage is a one minute sinusoidal voltage applied to the insulation. It is a function of BIL and is generally expressed by $4.5 \text{ BIL} - 15 \text{ kV}$ [3]. The power frequency withstand voltage is much lower than BIL and SIL values as evident in Table 2.1. The arrester must be able to withstand these voltages for an acceptable insulation performance [2]. It is seldom that the magnitude of the switching surge or lightning surge will exceed this voltage [2], [3], [29]. However, this does not consider persistent fast transient faults that occur in the system.

2.2.6 The role of surge arresters in power system's insulation coordination

Surge voltages can be generated by a lightning strike on a line and have a short time duration lasting several microseconds [2], [3]. These voltages are difficult to protect against as lightning strikes are unpredictable. In practice, adequate earthing is sufficient to protect against these voltages [26]. Surge arresters are critical in the insulation coordination as they mitigate the impact of overvoltages in the power system as illustrated in Figure 2.1.

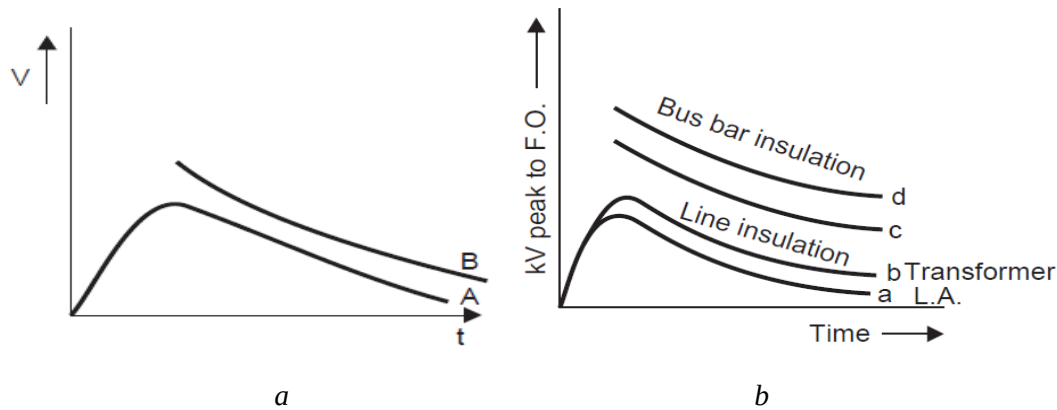


Figure 2.1: (a) Typical volt time characteristic showing surge arrester (A) and the protected equipment (B), (b) position of the surge arrester (a) relative to other system's components (b-d) insulation levels [22]

Figure 2.1a shows the surge arrester (A) that protects device B for example a transformer. Similarly, the surge arrester in Figure 2.1b must protect the transformer, lines, and busbars. Insulation coordination is therefore required to ensure that less critical equipment fails first. In this case, surge arresters will protect all the expensive equipment. Insulation coordination is reached when the equipment's insulation levels are selected in such a manner that abnormal conditions do not immediately lead to the failure of expensive equipment i.e., transformers, circuit breakers, etc. [22].

The objective of insulation coordination is to ensure that no part of the system is left vulnerable. In practice, insulation coordination is a delicate exercise that can be strengthened by other interventions. These include equipment condition monitoring i.e., partial discharge measurements to assess the intensity of corona, maintenance, infrared scanning, measurements and aerial or ground inspections. However, these tasks must be exercised in a cost-effective manner as absolute coordination is not possible. Power engineers must assess reliability costs based on customer needs and within budget constraints. Insulation coordination is done on critical equipment at risk such as transformers.

2.3 Insulation coordination methods in power systems

There are two methods that can be employed to achieve insulation coordination, namely conventional and statistical methods.

2.3.1 Conventional method

The insulation level of different types of equipment connected to the power system must be higher than transient overvoltages in the system [30]. Magnitudes of transient voltages are usually limited to a protective level of the protective device as shown in Figure 2.2.

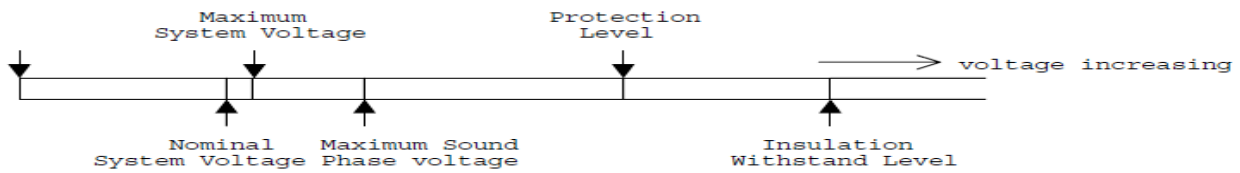


Figure 2.2: The operating voltage levels and protection level as the voltage in the system increase [30]

The impulse voltage insulation level is established at 15 to 20% above the protective level [26], [30]. Conventional methods involve protecting the feeder and the load whilst ensuring that adverse system interruptions are kept to a minimum. This is normally done by using gaps or discs in insulators as illustrated in Figure 2.3.

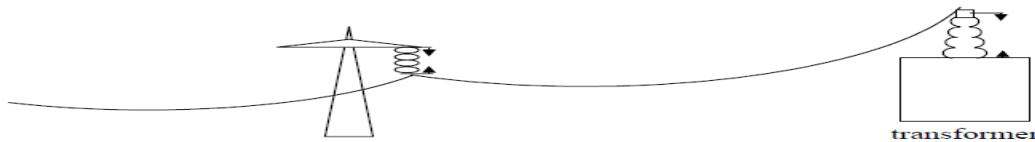


Figure 2.3: Coordination methods by using gaps [30]

The insulation coordination gap for a transformer must ensure the transformer's protection under all conditions. Line gaps protecting the line insulation can be set to a higher characteristic to avoid unnecessary interruptions [30]. The coordination in Figure 2.3 may be sufficient in protecting a distribution pole mounted transformer. However, this coordination is not effective in protecting large transformers against very fast transient and lightning voltage surges, thus a surge arrester would be required.

2.3.2 Statistical method

In transmission voltages, the length of insulator strings and clearances in air increase linearly with voltages [30]. In higher voltage systems, switching overvoltages tends to be dominant and require properly designed switching devices such as surge arresters [12], [3], [30]. Statistically, the overvoltages in the power system are higher at lower voltages as shown in Figure 2.4a. These overvoltages are reduced as the system voltage increases as shown by [30] in Figure 2.4b. These may explain higher incidences of 88 kV surge arrester failures in the EGTN rather than 275 kV and 400 kV surge arresters in this network.

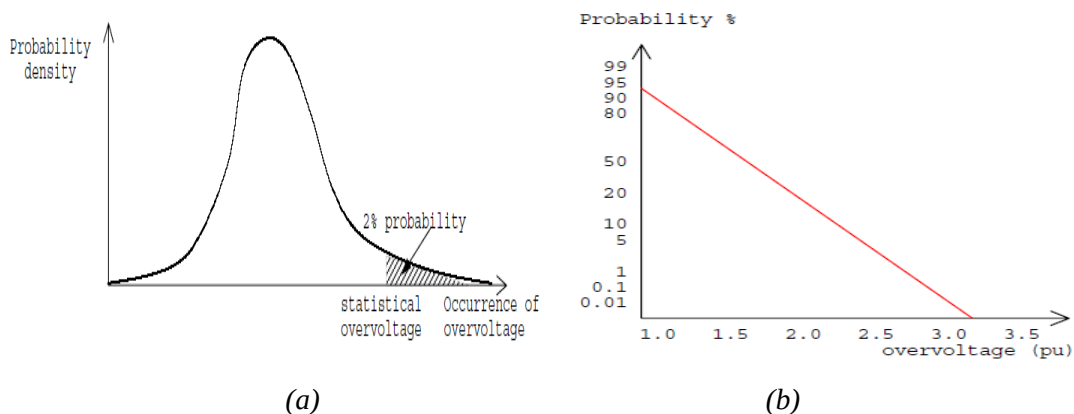


Figure 2.4: (a) The statistical impulse voltage and (b) the probability of voltage exceedance [30]

The statistical method is based on a statistical distribution of overvoltages; thus, it is not economical to provide insulation above a certain overvoltage value [30]. In practice, the overvoltage distribution characteristic is modified using switching resistors which damp out the switching overvoltage [30]. This ensures arresters are set to operate on higher switching overvoltages resulting in low probability of failure [30]. To apply the statistical insulation coordination method, we must evaluate the risk factor.

The risk factor deals with the quantification of the risk of failure of insulation through numerical analysis. The risk of failure of insulation depends on the overvoltage density function and the probability of insulation failure (Figure 2.5) [30]. The risk of flashover per switching operation is the area under the curve as illustrated in Figure 2.5. The statistical insulation coordination method is important where surge arresters are installed to protect dynamic loads such as traction loads. This requires an understanding of the position of the surge arrester and all dangerous voltages that it must protect against. The relationship between the critical voltages and transient voltages is important and can be expressed:

$$\frac{\Delta t}{x} = \frac{k}{vC} \left(1 - \frac{e_0}{e}\right) \dots\dots\dots (2.2)$$

where,

e_0 : is the critical voltage

e : is the voltage at any given time, t

Δt : is the change in time, t

k : is a constant, $0 < k \leq 1$,

x : position of the surge as it progresses on the line

Equation (2.2) allows us to calculate precisely the protective distance required when we know the parameters of the surge arrester shown in Figure 2.6.

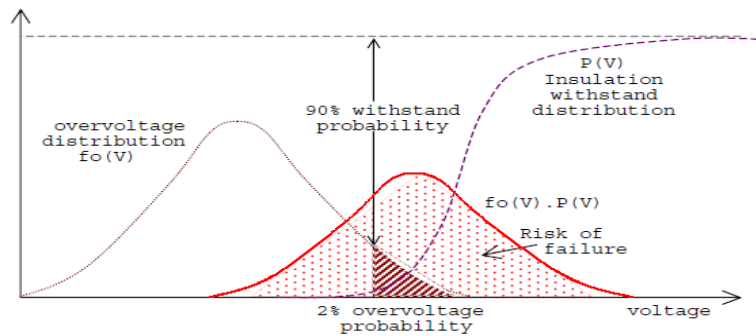


Figure 2.5: The evaluation of risk factor [30]

Surges in the power system are random, therefore surge arresters must be positioned and configured in such a way that the propagation of surges is minimized. Therefore, different voltages, mainly temporary overvoltages, must be understood and analyzed statistically. This ensures that the network is fully protected against their adverse effects [28], [30].

It is common engineering practice to match surge arresters used on the customer side with those at customer end. However, this is not always possible, therefore thorough investigations must be carried out when surge arrester failure(s) occur. The locations and distances of protective devices from loads are important in insulation coordination [26], [30]. Surge arresters are installed close to the equipment they protect (Figure 2.6) and are positioned and configured in such a way that the propagation of surges is statistical. This allows for statistical analyses of the different voltages, mainly temporary overvoltages to ensure that the network is fully protected against their adverse effects [28], [30]. Also, a protective distance must be maintained to effectively protect an equipment [26]. This also protects all loads that are fed from such equipment. Protective distances are calculated by (2.3) [26].

$$L_{\max} = \frac{V \left(\frac{LIWL}{1+M_p} \right) - U_{\text{res}}}{2S_t} - H_{\text{arrester}} + H_{\text{structure}} \dots\dots\dots (2.3)$$

Where,

V is the nominal voltage,

LIWL is the lightning impulse withstand level,

M_p is a protective margin with a minimum value of 0.2 as per IEC 60099 recommendations,

U_{res} is the residual voltage of the arrester,

H is the height of the arrester & structure and

S_t is the steepness of the incoming wave in kV/μs typically 2000 kV/μs.

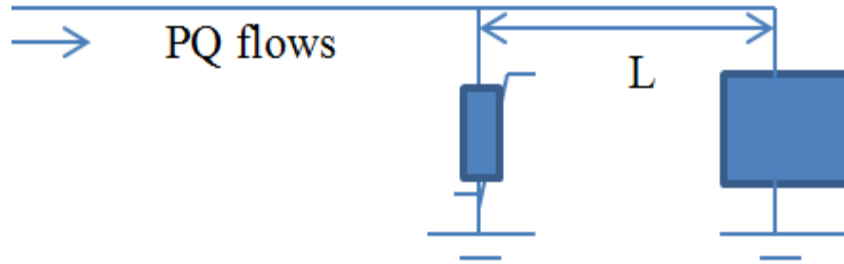


Figure 2:6: Typical application and location of a surge arrester

In transmission systems coordination is achieved by applying metal oxide gapless surge arresters with appropriate safety margins to limit the overvoltage stresses to below lightning and switching impulses [26].

2.4 Utilization of metal oxide surge arresters in insulation coordination

Lightning surges present highest surge risks to insulation coordination. Low currents can generate a 1000 kV surge in the power system [28]. This is enough to cause insulation flashovers, puncture metal blocks in metal oxide surge arresters and even destroy surge arresters [28]. These surges can travel down the system even after the arrester has operated and can cause damage to the system. This is because open circuits double the surge's amplitude due to reflections [12, 28].

Switching voltage surges are not the only determining factor in the insulation requirements of apparatus [31] but are important in evaluating the performance of surge arrester parameters. These surges must be evaluated against surge arrester continuous operating voltages. However, these voltages are much lower than surges that may arise in the power system as these surges have very short durations and may not necessarily lead to the sudden destruction of the surge arrester. The continuous operating voltage of an arrester can be expressed in terms of its rated voltage, U_r such that the arrester protects the equipment against severe contingencies with a protection ratio, K_s [32]. The limits of the protection ratio, K_s are assessed by evaluating the impulse surge on the surge arrester as follows:

$$\frac{BIL}{SP_i} = K_s \dots\dots\dots (2.4)$$

where, SP_i is the residual voltage when the nominal discharge current flows through the arrester. Residual voltages are determined from voltage – current characteristics as shown in Figure 2.7.

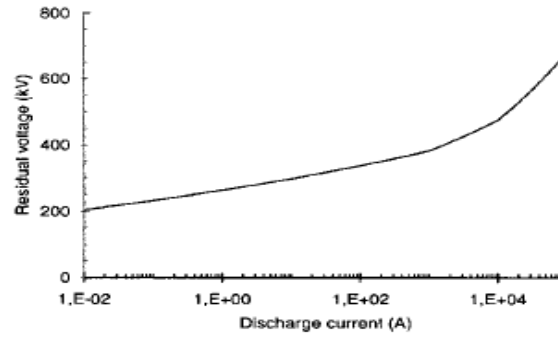


Figure 2:7: Voltage characteristics of an arrester [32]

2.5 Power system surges

A voltage surge or transient voltage is a sudden rise in the voltage for a very short duration usually less than two minutes on the power system [12], [33]. The characteristic of a voltage surge is described as the ratio of t_1 and t_2 time durations where t_1 is the time taken by the surge to reach its peak and t_2 is the time taken for the surge to dissipate as shown in Figure 2.8. The ratio of t_1 and t_2 is expressed as t_1/t_2 such that a $1/50 \mu s$ voltage surge implies this surge reaches its peak in $1 \mu s$ and decays in $50 \mu s$. It should be noted that this surge is faster than for example the $8/50 \mu s$ voltage surge.

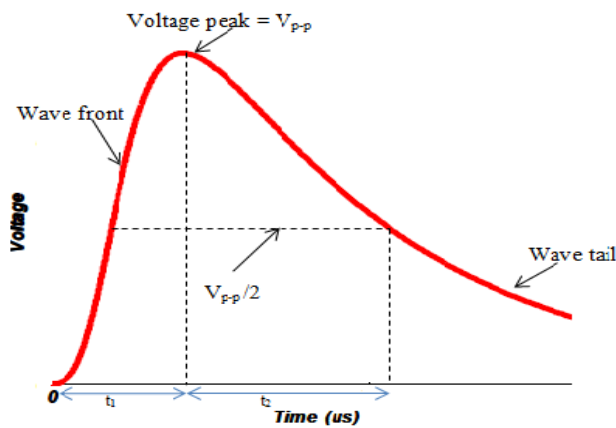


Figure 2:8: A typical characteristic of the voltage surge with a voltage peak, rise time t_1 , and decay time t_2

The wave front of a voltage surge is steeper and dangerous as it reaches its peak within a very short period, t_1 . The wave tail decays slowly; this is dangerous as it causes the surge to remain in the power system longer [12]. This characteristic overstresses the insulation of a surge arrester and may result in the exceedance of its EAC [22], [12]. A surge's peak voltage can exceed the protective level of surge arrester as the surge develops and its wave tail takes longer to dissipate. These characteristics are crucial in the performance evaluation of surge arresters, their selections and the overall evaluation of the power system's insulation coordination [2], [29].

2.5.1 Modelling power system surges

2.5.1.1 Introduction

Power systems surges are studied by understanding wave propagation models [28]. IEC and IEEE current or voltage impulse test waveforms used by manufacturers for testing protective devices use these models. Common impulse test models are Bewley lattice and Heidler models described in [28].

2.5.1.2 Bewley lattice surge models

Outdoor electrical equipment may be subjected to impulses due to lightning where the BIL is used to establish the ability of the equipment to withstand lightning impulses, i.e., power frequency voltage as noted in [3]. To fully understand the BIL, it is useful to describe this voltage in the context of the lightning surge. This voltage can be modelled by a test wave which is a double exponential impulse with a crest value reaching the system maximum voltage.

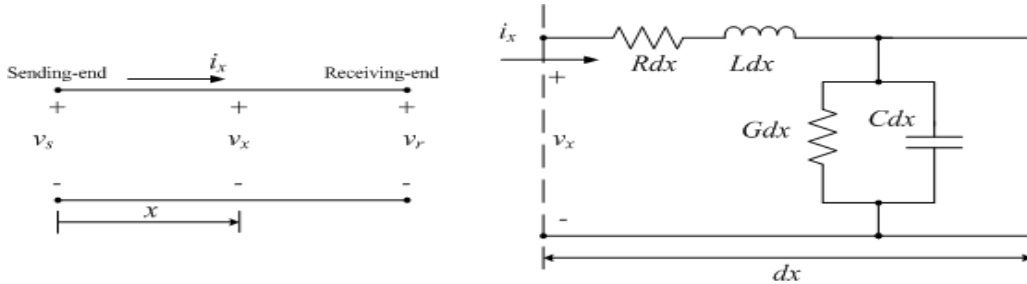


Figure 2:9: Model for transmission line wave propagation [28]

A long line model of approximately 350 km as shown in Figure 2.9 is recommended in studying surge voltage behaviors [28]. This model is a good representation of power lines for high frequency impulses such as lightning surges [28]. This model is described mathematically in [28] as a second order ordinary differential equation (ODE) as follows:

$$\frac{1}{LC} \frac{d^2 v(x,t)}{dx^2} = \frac{d^2 v(x,t)}{dt^2} \dots\dots\dots (2.5)$$

This equation describes the behavior of lightning on transmission lines and contains both reflection and refraction components of the lightning wave [28]. This model is sufficient to study effects of lightning on the performance of surge arresters; however, advanced computer tools are required to analyze it because of its complexity. In practice, transmission lines are generally not very long and the model in equation (2.5) was found by [34] to be inaccurate when ferroresonance is considered. This make this model unsuitable for the lengths of transmission lines in the EGTN which are relatively short.

2.5.1.3 Heilder's surge functions

There are many travelling wave differential equations and their respective solutions, but the Heilder's surge function is the most accurate [28]. This function is illustrated in Figure 2.10(b) and provides insights on the behavior of lightning and it impacts on surge arresters.

Heilder's surge function is described mathematically by [28] as:

$$f(t) = \left(\frac{F}{N}\right) \left(1 - e^{-t/\tau_1}\right)^k e^{-t/\tau_2} \dots\dots\dots (2.6)$$

where:

$\frac{F}{N}$ is the amplitude of the surge function

k, τ_1 and τ_2 are parameters which determine the steepness and decay of Heilder's surge function

Heilder's surge functions are accurate, easy to create in simulation tools and are used with surge arrester voltage – time curves. This is critical and useful in the performance evaluation and selection of surge arresters [28].

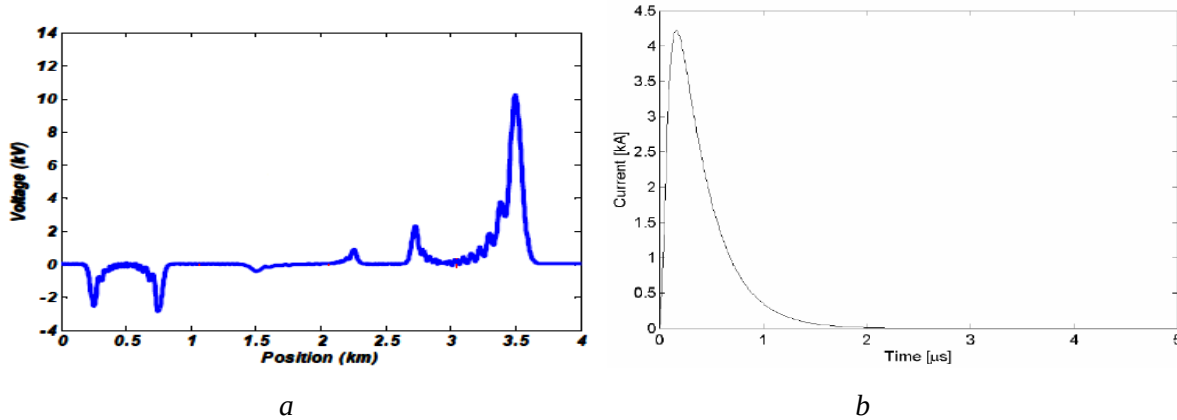


Figure 2.10: A switching surge waveform (a) and (b) Heilder's lightning surge [28]

A typical voltage surge is illustrated in Figure 2.10 (a) where the network is subjected to voltages at the end of the feeder. Surge functions are created using signal generators excluding the impact of other external voltage or current sources. They do not consider characteristics and the behavior of the actual network, thus may underestimate or exaggerate surge voltage or current amplitudes. This will result in inaccurate surge arrester performance evaluations of surge arresters in the EGTN.

2.6 Causes of overvoltages in power systems

There are several instances when power system elements such as generators, transformers, transmission lines, insulators, etc. are subjected to overvoltages. These overvoltages may be caused by lightning, switching, open circuiting, etc. [12]. They adversely impact the performance of protective devices such as surge arresters [22], [35], [3] as they can cause insulation breakdown of the equipment [12]. Overvoltages in the power system are broadly divided into internal and external causes.

2.6.1 Internal overvoltage causes

Internal overvoltage causes do not produce surges of large magnitudes as surges due to internal causes do not increase system voltage to twice the normal operating value [3]. The internal causes of overvoltages are due to switching surges, insulation failure, arcing ground, and resonance [12].

2.6.1.1 Switching surges

Switching surges are caused by switching operations such as opening and closing of network circuit breakers [12]. A loss of one phase voltage in a three-phase transmission line causes the remaining phase voltages to rise causing phase to ground faults. Malfunctions, single end tripping and auto-reclosing in line circuit breakers may result in switching surges [22] and may cause protective devices such as surge arresters to fail.

Arcing ground or thermal run away caused by tower back-flashovers in non-effectively earthed systems results in severe voltage oscillations which can be three to four times the operating voltage [12], [36]. This requires footing resistances of not less than 10Ω for bonded structures and about 20Ω for non-bonded structures [3], [37]. Where structures are not bonded to the substation earth mat, footing resistances may exceed design limits. However, these back-flashover voltages are very seldom in the substation vicinity as terminal structures are solidly bolted onto the earth mat.

2.6.1.2 Resonance

This condition arises when inductive and capacitive reactances are equal [38] such that:

$$X_L = X_C \dots\dots\dots (2.7)$$

which yields

$$\omega L = \frac{1}{\omega C} \dots\dots\dots(2.8)$$

resulting in the following expression:

$$\omega = \frac{1}{\sqrt{LC}} \text{ or } f = \frac{1}{2\pi\sqrt{LC}} \dots\dots\dots(2.9)$$

Where:

ω : is the angular frequency in radians per second,

f : is the natural frequency in Hertz,

L : is the inductance in Henries and

C : is the capacitance in Farads

Long transmission lines result in large capacitances that cause increased line receiving voltages [19], [34] as illustrated in Figure 2.11 (b).

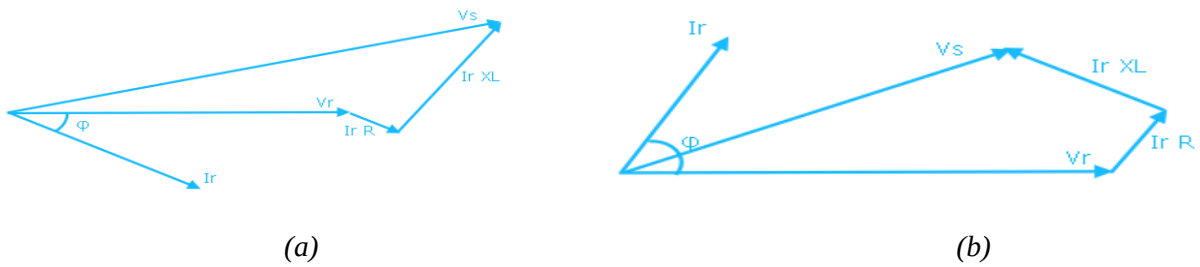


Figure 2:11: The normal transmission line phasor diagram without resonance (a) where $V_s \geq V_R$ and (b) abnormal condition (resonance) where $V_s \leq V_R$ [12]

Resonance also causes severe stresses on the insulation of all the equipment connected to the same circuit and surge arresters are normally the most vulnerable apparatus in substations due to their low temporary overvoltage withstand capabilities [38].

2.6.2 External causes of surges in power systems

The most common external cause of power system's voltage surges is lightning [12] arising due to electric discharge between cloud(s) and earth [22], [12], [39]. Lightning discharge currents range from 10 to 90 kA [12], therefore it is necessary to evaluate lightning discharge capability of arresters in the EGTN to ensure that they can withstand lightning discharge currents.

Chapter 3.

Power systems reliability

In this chapter, reliability evaluations and computation of reliability indices in power systems are discussed. Different approaches in distribution and transmission reliability evaluations are also highlighted. The impact of component failures and surge arrester failures on Eskom's cost of unserved energy is also briefly highlighted.

3.1 Introduction

Power system reliability is the ability of the power system to deliver an uninterrupted service to customers [40]. The reliability of the power system can be broken down into power system security and adequacy [40], [41]. Power system security evaluates the ability of the system to respond to perturbations. Power system adequacy evaluates the capability of the network to supply customer load demands [41].

Regulated power systems are designed, operated, and maintained according to regulations stipulated by the licensor. The National Energy Regular of South Africa (NERSA) prescribes minimum requirements that energy utilities must meet. The transmission code prescribes minimum requirements to be met by National Transmission Companies (NTCs) in the power system planning, design, and operation to limit the adverse effects of network faults [4], [42].

Power system reliability indices are used to evaluate the performance of the power system to ensure compliance with prescribed minimum standards [16]. The size and complexity of the power system makes overall network's reliability analysis cumbersome. Thus, segments of the power system are appraised [17], [43]. In Eskom for example, power system reliability indices used to appraise the network are different for each business division (Generation, Transmission and Distribution divisions).

3.2 Power systems reliability evaluation methods

There are two methods that can be utilized in the evaluation of the reliability of the power system, namely analytical and simulation methods [44]. The former is applicable in simpler networks whilst the latter assesses large networks. Analytical methods represent the power network in its simplified form and the evaluation of reliability indices is derived from direct mathematical solutions [1], [41]. Simulation methods are used to simulate actual processes and random behavior of the power network to estimate its reliability indices [1].

In the simulation method probability distribution functions are used to estimate reliability indices by counting the number of times an event occurs [16], [45]. Analytical methods always give the same numerical results for the same system and input data. The computation of reliability indices using the analytical method takes longer as the physical system needs to be understood [1]. Simulation methods can provide a range of output parameters quicker. This method relies on randomly generated numbers and a high number of simulations to accurately compute reliability indices [16], [45], [46]. The superiority of the simulation method over the analytical method was illustrated by Shavuka et al. [1] in Table 3.1.

Table 3.1: Comparison of analytical and simulation methods in the Philippi test system [1]

Reliability Indices	(A)	(S)	Difference %
SAIFI (Int./Cus.yr)	0.3417	0.3339	-2.28
SAIDI (hrs/Cus.yr)	4.6269	4.7230	+2.08
CAIDI(hrs/Cus.Int.)	13.5408	14.1011	+4.14
ASAI	0.9995	0.9995	0
ASUI	0.0005	0.0005	0
ENS (MWh/yr)	5.3171	5.4275	+2.08
AENS (kWh/Cus.yr)	6.96	7.1	+2.01

Reliability evaluation methods can be modelled and evaluated by testing them on the RBTS with necessary data as model inputs [47]. Seemingly both methods can be applied and compared in the EGTN to evaluate the impact of surge arrester failures on the transmission performance.

3.2.1 Analytical method

This method assesses load points behavior if a particular component fails. Failure rate (λ), outage time (r) and unavailability (U) are required inputs into this model [1], [41], [47]. These parameters are then used in the computation of common distribution reliability indices, namely SAIFI, SAIDI, CAIDI, CAIFI and ASAI [1], [41], [48], [33].

3.2.2 Simulation methods

In this method probability distribution functions can be created using Monte Carlo simulations using the statistical interpretation of the parameters in the network. These parameters can be used to calculate probability distribution means and standard deviations [1]. Examples of probability distributions that can be generated from simulation methods are shown in Figure 3.1.

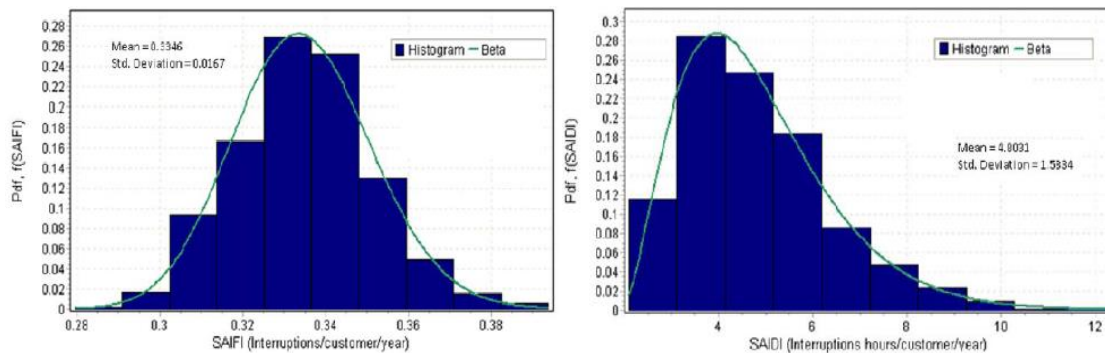


Figure 3.1: Examples of probability density functions created by simulation methods [1]

The probability distribution behavior as shown in Figure 3.1 and computed reliability indices can be used to assess network performance. These probabilities can also be used in network performance benchmarking and investment decisions [1], [16], [45].

3.3 Transmission and distribution performance evaluations

3.3.1 Introduction

Transmission and distribution systems in South Africa must comply with power quality limits in NRS 048 and the grid code [4], [42]. Network reliability evaluations are formulated in accordance with NRS 048 and grid code requirements.

3.3.2 Reliability evaluation of the Eskom transmission system

The descriptions and considerations utilized in the Eskom's transmission performance assessment are defined in greater detail in [5]. The criteria utilized in Eskom's transmission system reliability evaluation are illustrated in Table 3.2. Each transmission grid's key performance indicators (KPIs) are monitored and reported on a yearly basis. Protection performance is discussed in greater detail in the protection performance KPI [49].

Table 3.2: Eskom Transmission reliability evaluation criteria [5]

Key performance indicators	Customer	Adequacy	Availability	Quality of Supply	Plant health	People & skills	
	PQ complaints	Systems Minutes < 1	SAIRI	Lines faults/100km	Plant Performance Index (PPI)	Operating errors	
	PQ contracts			Line faults per 100km per voltage class			
	PQ claims	Load Loss Events - Imports	Unplanned Circuit unavailability	Line faults per 100km (critical & unfirm)	Tx Maintenance Index		
	Customer response						
	NetCare	Number of major incidents	EAF (Imports)	Voltage Regulation	Maintenance Completed		
	GenCare	Number of major incidents	UU (Imports)				Waveform Index
				Power Quality Index			
				Voltage Harmonics			
				Voltage Unbalance			
	Primary Plant Failures	Busbar isolations	Protection performance (PPI)		Failure frequency		
	Severe Transformer Failures	Buszone Operations	Non System Faults (NSF)	IPS Number of Interruptions			
	Reactor Failures						
	Shunt Capacitor Failures						
	Series Capacitor Failures	Busstrip Operations	Systemem Performance Index (SPI)	Number of Interruption (NOI) Events			
	SVC Fauilures						
	Circuit Breaker Failures			Load Loss Events - Imports			
	Auxiliary Equipment Failures						

System Minutes (shown in Table 3.2) is one of the critical key performance indicators that measures the duration of network interruptions in transmission systems. This performance measure is computed by:.

$$\text{Systems Minutes} = \frac{\text{Load interrupted (MW)} \times \text{duration in hours}}{\text{Eskom Transmission network annual system peak (MW)}} \dots\dots\dots (3.1)$$

The Eskom transmission network annual system peak can be used to calculate Systems Minutes. Eskom transmission peak changes over the years based on load demand and other system constraints are shown in Figure 3.2.

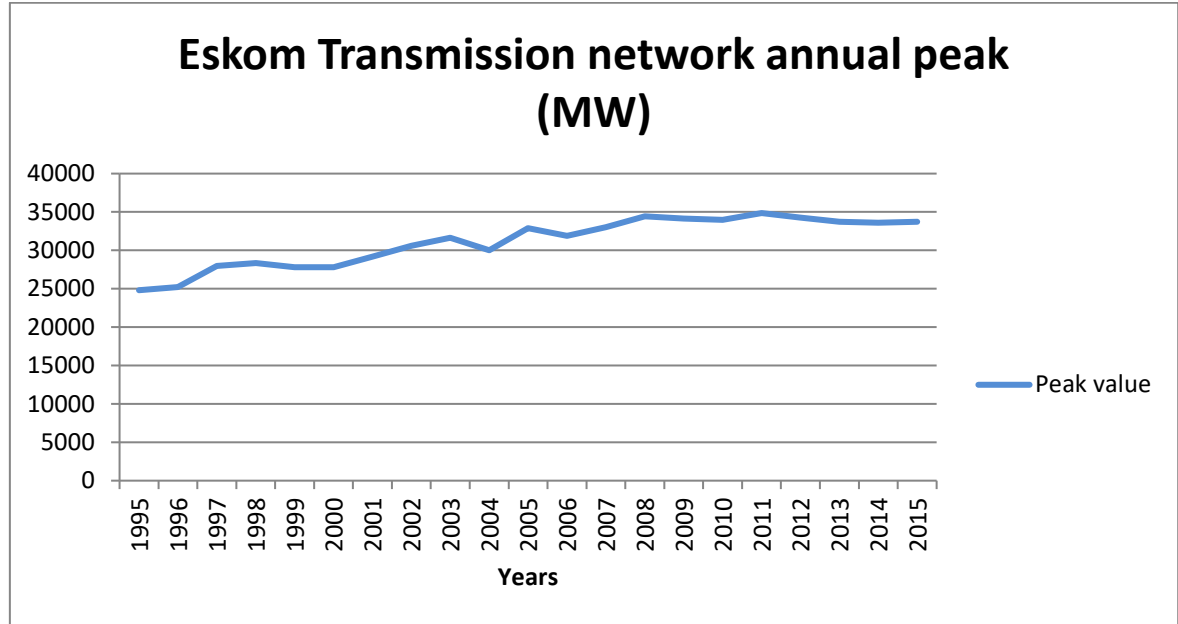


Figure 3:2: Eskom Transmission network annual system peak in 20 years [18]

The Plant Performance Index (PPI) gives an overall assessment of the state of plant performance in transmission. This includes number of plant failures, bus operations and protection operations. Each plant item is scored against its own associated alarm and level of criticality [5]. PPI monitoring over a long term is done as shown in Table 3.3. Each Grid assesses its current performance against targets set in the operational plan as shown in [50].

Table 3.3: East Grid transmission performance evaluation for financial years 2016, 2017 and 2018 [51]

Key Performance Areas and Indicators	2016/17 Plan	2017/18 Plan	2018/19 Plan
STAKEHOLDER AND CUSTOMER			
GenCare (%)	100	100	100
NetCare (%)	100	100	100
TECHNICAL PERFORMANCE			
Number of supply interruptions (NOI)	7	6	3
System Minutes lost < 1min	0.83	0.72	0.60
Major incidents (No)	0	0	0
Line faults (per 100km)	137	135	130
Unplanned Circuit Unavailability (%)	0.35	0.35	0.35
Plant Performance Index (%)	90	90	90
Operating errors	1	0	0
Maintenance completed (%)	97	97	97
PROTECTION & ISOLATIONS			
System Protection Performance Index (SPI)	2	2	2
Non System Fault (NSF)	4	4	4
Auto Reclose Performance Index (ARPII)	3	3	3
Bus zones	4	4	4
Bus strips	2	2	2
PRIMARY EQUIPMENT FAILURES			
Transformer (Severe)	1	1	1
Transformer (Non-Severe)	2	2	2
Reactors	0	0	0
Shunt Capacitors	8	8	8
SVC	15	15	15
Circuit Breakers	5	5	5
Auxiliary items	4	4	4

3.3.3 Reliability evaluation of Eskom's distribution system

The reliability evaluation of the distribution network is carried out by assessing KPIs. These KPIs quantify the loss of supply in terms of the frequency and duration. They also include the amount of installed capacity and the number of customers affected by events. The KPIs are dependent on the accuracy, consistency of the tracing of the events. These KPIs are set yearly for benchmarking and to ensure continuous performance monitoring as shown in Table 3.4. Reliability indices of the distribution network are computed based on voltage levels described in [4], [33]. A full description of Eskom's distribution system reliability indices is found in [33].

Table 3.4: KZN OU SAIFI performance as at 31 December 2016

Area	Target	SAIFI Year	%Above(+ve)/Below(-ve) target	SAIFI YTD	% Budget remaining
KwaZulu-Natal Operating Unit	21.6	22.76	5.36%	17.38	19.56%
Empangeni Zone	23.63	28.55	20.84%	23.67	-0.19%
Newcastle Zone	20.22	20.37	0.72%	14.40	28.79%
Pietermaritzburg Zone	19.63	19.38	-1.23%	14.32	27.05%

The EGTN is fed from transmission and distribution networks thus respective reliability indices need to be evaluated. The biggest contributions to poor network performance are faults which are due to external factors such as lightning [8], [52]. In South Africa, lightning prevalence is higher in autumn and spring seasons as noted in Figure 3.3.

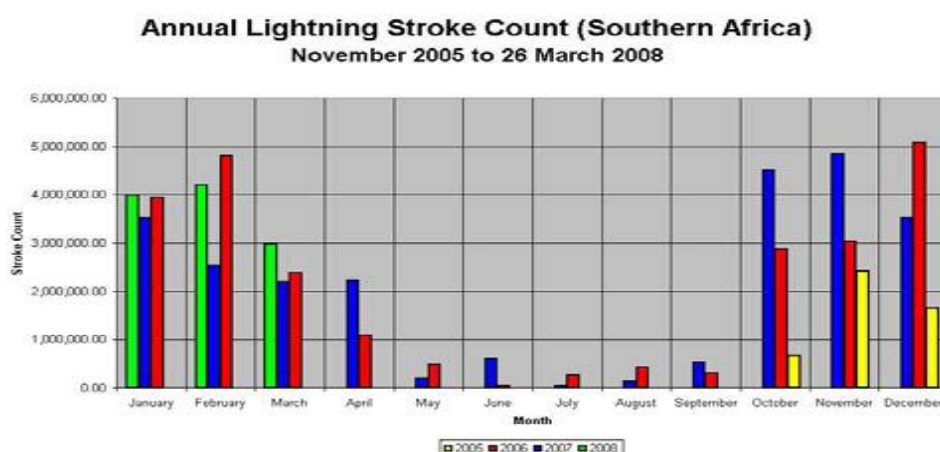


Figure 3.3: Southern African annual stroke count for the period 2005 - 2008 [53]

Ground flash density is higher in inland areas as shown in Figure 3.4. This makes lightning ground flash density to be a significant factor in analyzing surge arrester failures. Moreover, the EGTN is in Newcastle inland areas which have high lightning prevalence. Investigating surge arrester failures in the EGTN requires an assessment of whether a correlation between these failures and lightning events exist.

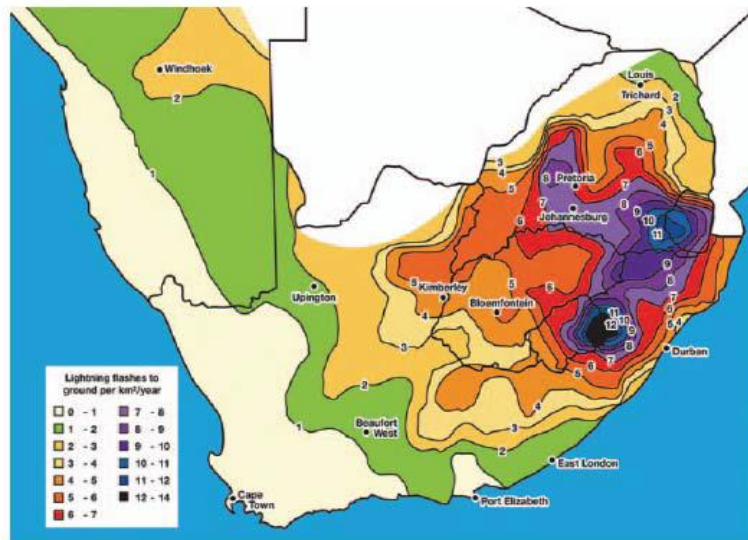


Figure 3:4: South Africa’s ground flash density map showing higher values in inland areas [52]

3.3.4 Determination of unserved energy in utilities

Network interruptions result in the utility not supplying energy to customers. The cost of unserved energy (COUE) is evaluated based on network interruptions [41], specifically, the energy not supplied due to an unplanned outage of short duration [44]. At the sectoral level, COUE reflects the value (in a country’s currency) per kWh of the electrical energy consumed by an economic sector (Figure 3.5).

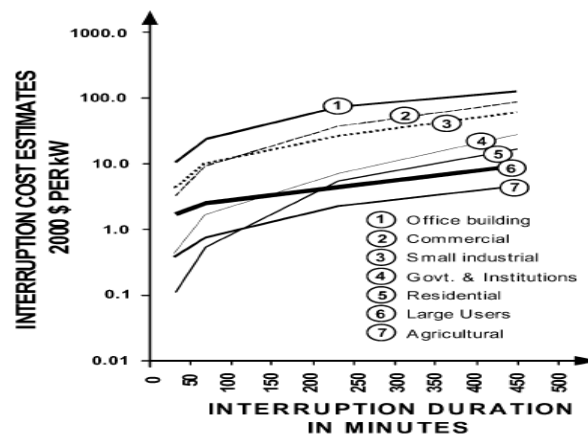


Figure 3:5: Sector damage functions of the Canadian distribution network [41]

Network planners must ensure that the expansion of the network is structured and that their network plans adequately meet future electricity demands [54]. This requires balancing COUE against the cost to supply energy [54]. It is for these reasons that during electricity price determination, utilities explain to customers and regulatory bodies their cost of unserved energy methodologies. Customers are at the heart of this process as their comments through public hearing must be collated before final tariff adjustments are granted [54]. Thus, methodologies employed for COUE determinations must meet Grid Code requirements [54], and must be based on a reasonable reliability level to customers and their expenditure on electricity costs [41].

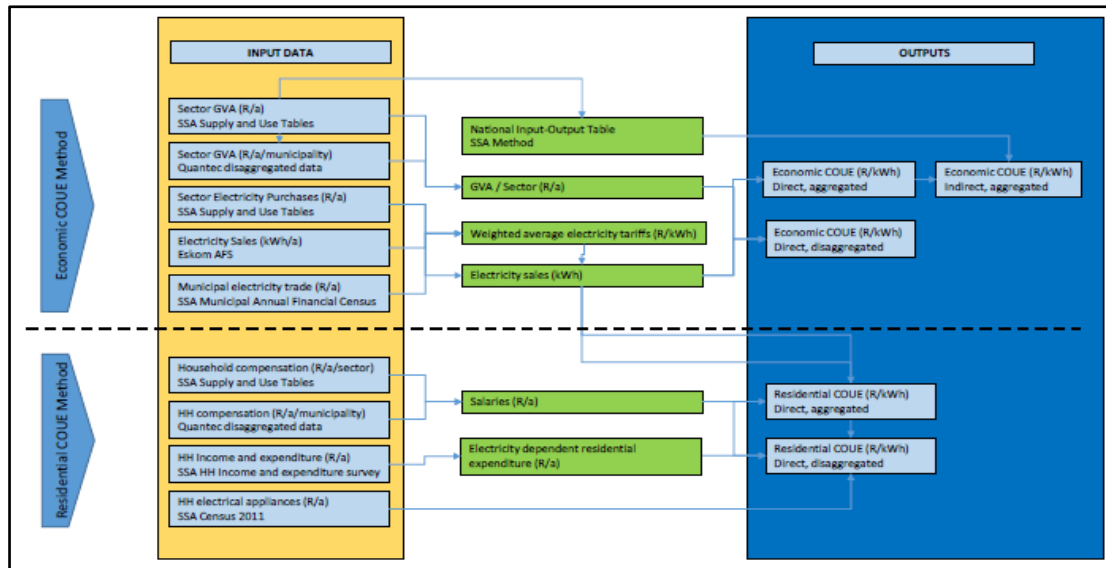


Figure 3:6: Eskom's cost of unserved energy determination methodology [54]

In most cases, COUE is determined on a sector-by-sector basis i.e., residential, agricultural, etc. as illustrated in Figure 3.5. This requires data collected through surveys to assist in the creation of sector damage functions [55]. The duration of individual customer load point interruptions assists in sector interruption costs evaluations [41]. Sector damage functions are aggregated to give a final country's cost of unserved energy. Various methodologies for estimating and interpreting the concept of COUE exist [55]. Each method has its own advantages and disadvantages [54], [55]. Eskom determines the COUE using a macro-economic method and this COUE is used in application for tariff price adjustments. This assesses the COUE from the country's gross domestic product as shown in Figure 3.6. The current COUE value in South Africa is R75/kWh [54].

Chapter 4.

Traction systems

This chapter discusses the topology of traction systems and their distinct features in comparison to normal real loads. The characterization of these networks, the challenges they pose in the grid's compatibility limits, and the potential remedies that can be adopted are also discussed. The goal of this chapter is to highlight the considerations to be made in modelling traction networks to evaluate the impact that these networks have on surge arrester selections and performance.

4.1 Introduction

Railway systems are an integral part of power system components due to the interdependence between electricity and transport sectors. These sectors drive economic growth as electric trains are mainly powered from power grids [24]. The dynamic nature of the traction networks creates performance challenges [19]. In this research, these challenges are studied to assess the impact of traction systems on the power grid surge arresters.

4.2 The structure and features of traction systems

A traction system involves an AC distribution line fed from a power grid usually operating at 88 kV or 132 kV as shown in Figures 4.1 and 4.2. Traction substations transform these voltages to 25 kV or 27.5 kV levels, and the load (train) is fed via the catenary. Traction systems have the following characteristics [56]:

- Nonlinear load(s) and produces high order harmonic,
- Negative sequence currents,
- Network voltage fluctuations,
- High reactive currents and
- Low power factors

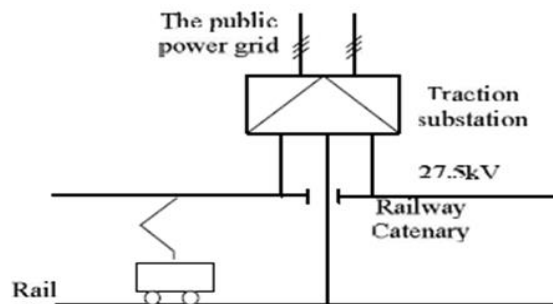


Figure 4:1: The structure of the power grid and traction system [24]

These characteristics make the power system more dynamic and requires that surge arresters in traction networks are carefully selected. The characteristics of the traction system and the prevalence of surges and faults in the network must inform the design, performance evaluation and selection of surge arresters in power grids feeding traction loads.

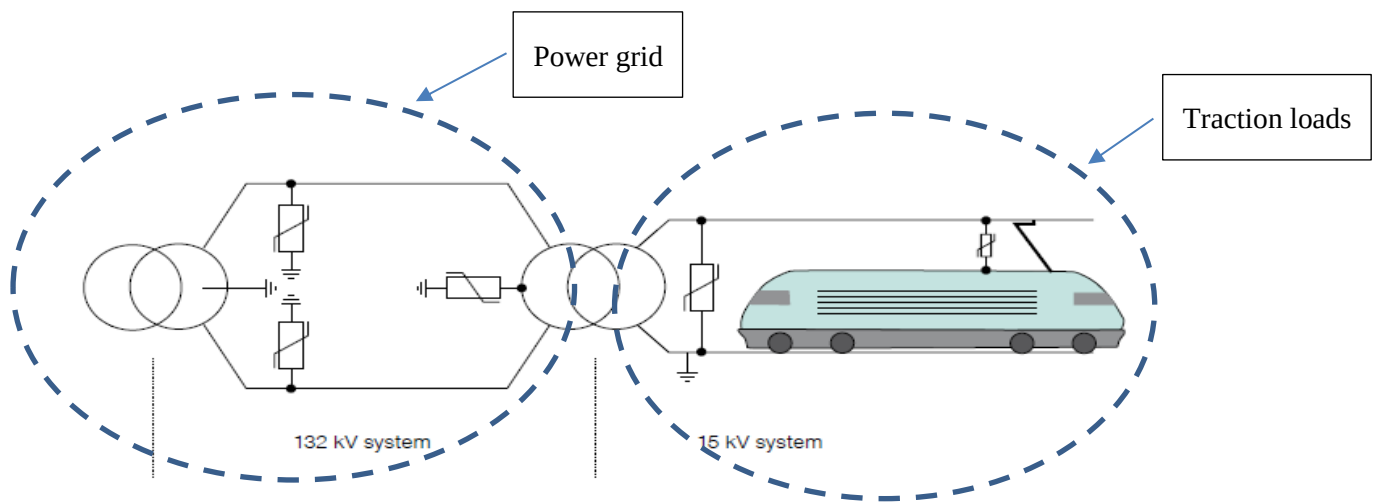


Figure 4:2: Schematic representation of a railway system and the application of surge arresters [57]

4.3 Impacts of traction loads on the power system's quality of supply

Voltage limit deviations are due to network faults, outages, voltage dips, current and voltage harmonics which have adverse impacts on the quality of supply delivered to customers. Voltage limits are categorized in the NRS 048-2 standard [4]. Traction loads create power quality of supply problems [56] such as:

- Negative sequence currents which generate heat and lead to protection devices maloperations.
- Harmonic currents which also generate heat in electrical devices such as transformers and lead to partial discharges on flexible alternating current transmission systems (FACTS) devices.
- Reactive currents which suppress the power capability of traction substation transformers.

4.3.1 Evaluation of voltage unbalances in power networks

Voltage unbalances arise in polyphase systems when the magnitudes of one or more phase voltages are not equal [5] and have unequal phase angles [4]. Voltage unbalances cause problems to customer equipment such as motors and variable speed drives. Utilities measure voltage unbalances as the percentage of sites exceeding the voltage unbalance limits over a specific period [4], [49]. Voltage unbalances are computed by the following expression:

$$UB = \frac{V_n}{V_p} \times 100\% \dots\dots\dots (4.1)$$

where:

UB is the voltage unbalance,

V_n is the negative sequence voltage, in volts and

V_p is the positive sequence voltage, in volts.

Voltage unbalance limits are specified to ensure that standard design voltages of equipment are not exceeded [4], [5]. In Eskom, voltage unbalance limits are set at 1.4% for business performance limits but must be within a 2% statutory limit [58]. Voltage unbalances caused by traction loads have adverse impacts on the performance of the transmission and distribution systems. The absence of voltage unbalance detection protection in the EGTN surge arresters may cause voltage unbalances to overstress these surge arresters. This requires that voltage unbalances around times when surge arrester failures occurred in the EGTN be assessed.

Figure 4.3 shows voltage unbalances when a 400/88 kV, 160 MVA transformer supplying traction loads at Umfolozi substation in the EGTN was taken out of service. It can be noted that voltage unbalances exceeded the 1.4% limit as agreed between customers and the East Grid in [59].

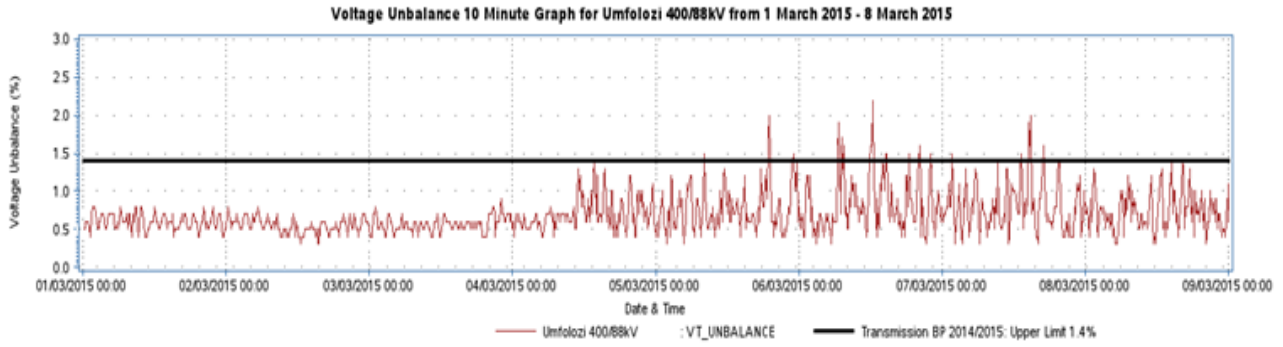


Figure 4:3: Voltage exceedances due to the voltage unbalance at Umfolozi substation when one transformer was taken out of service [60]

Regenerative braking of the locomotive leads to voltage distortions or voltage unbalance factors (%) in traction systems. These distortions are described mathematically by [56] as follows:

$$\varepsilon_V = \frac{\sqrt{3} V_L I_{1(2)}}{10S_k} \times 100\% \dots\dots\dots (4.2)$$

where:

ε_V is the voltage distortion factor

V_L is the line voltage of the power network in kV,

$I_{1(2)}$ is the fundamental negative sequence current of the traction load in amperes (A),

S_k is the short circuit capability in MVA

Traction voltage distortions are small when loads are high and vice versa as shown in Figure 4.4. The relationship between the load and the degree of voltage unbalance factor is shown in Figure 4.4.

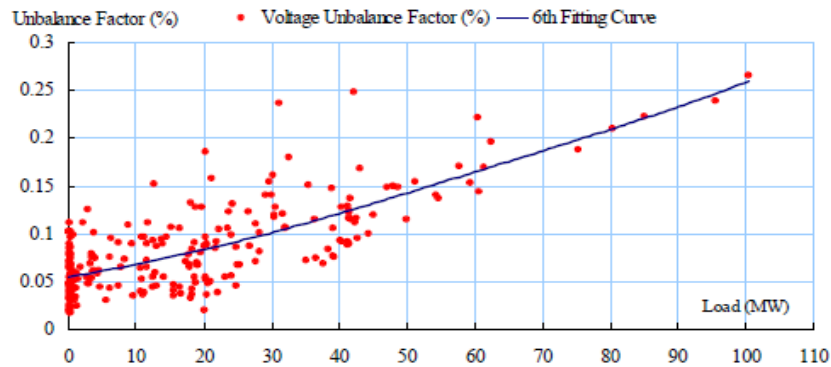


Figure 4:4: Typical voltage unbalances in traction networks [19]

4.3.2 Evaluation of current unbalances in power networks

The distribution of currents in a traction system is modelled and illustrated by [61] in Figure 4.5. This model appears accurate for modelling the EGTN as it shows the traction load as a nonlinear RLC circuit as recommended by [57].

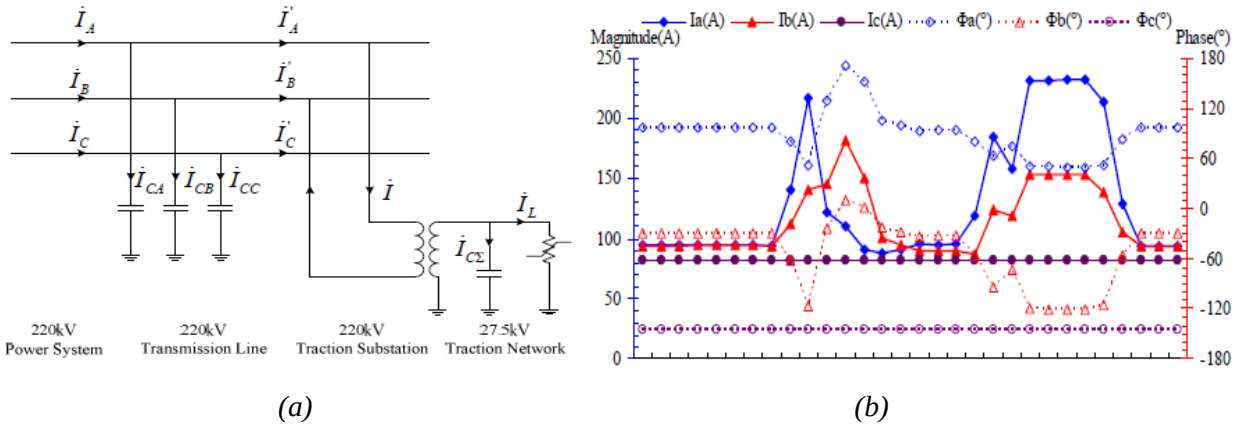


Figure 4.5: (a) Equivalent model of the traction system, (b) Load currents of Wuhan-Guangzhou traction system (China) [19]

The Wuhan-Guangzhou traction network considers different modes of speed in the train. These include acceleration, deceleration and braking of the train. Currents flowing in this network vary substantially as seen in Figure 4.5(b) leading to voltage unbalances in the network. Voltage unbalances can also be evaluated by calculating the unbalance factor as the traction load absorbs or injects power into the grid [19]. Figure 4.4 indicates a strong correlation between the voltage unbalance factor and the power drawn by the traction system.

The following equivalent system voltage of the Wuhan-Guangzhou traction system was proposed by [19].

$$E'_s = \frac{X_c}{X_c - X_s} E_s \quad (4.3)$$

where X_c and X_s are cable and system reactance respectively, and E_s is the system's voltage which is normally 88 kV or 132 kV in South Africa. The system's equivalent impedance can be expressed as follows:

$$X'_s = \frac{X_c}{X_c - X_s} X_s \quad (4.4)$$

The system's short circuit capacity (S_s) can be expressed as:

$$S_s = \frac{U_T}{X_s} E'_s \quad (4.5)$$

where, U_T is the traction system's traction voltage.

Denoting the load absorbed by traction as P_T , such that $P_T = U_T$ and observing that $\frac{S_s}{P_T} \gg 1$, the voltage unbalance factor, K_u can be expressed as [19]:

$$K_u = \frac{U_b^{(2)}}{U_b^{(1)}} \quad (4.6)$$

where, $U_b^{(1)}$ is the positive sequence voltage and $U_b^{(2)}$ is the negative sequence voltage

The expansion of equation (5.6) yields,

$$K_u = \frac{X'_s}{\sqrt{E_s'^2 - (X'_s I^{(1)})^2}} = \frac{|P_T|}{\sqrt{3} S_s} \quad (4.7)$$

Equation (4.7) shows that the voltage unbalance factor increases when the traction load is heavy and reduces with increasing fault levels. This is important in the study of surge arresters in the EGTN as lower fault levels may lead to surge arrester failures as noted in [19]. Furthermore, traction networks may cause voltage and current unbalances resulting in undesirable surge arresters' performances due to varying train speeds and locations. However, modelling this system with these considerations leads to complications as the resultant harmonic spectrum of two or more trains cannot be derived. This is because the harmonic spectrum cannot be

derived by simply adding each train's contribution one by one [62]. Single phase systems and traction drives generate high negative and zero sequence and harmonics currents into the grid [62] resulting in poor quality of supply and reliability of the grid. Therefore, detailed traction's RMU parameters are required for system modelling but these are usually not known to the power utility.

4.3.3 Evaluation of current and voltage harmonics in traction systems

Traction substations are integrated into strong power system supplies as shown in Figure 4.6(a) with large short circuit capacity [19]. This is because traction systems have AC to DC converters which utilize rectifiers that cause significant harmonic currents and poor power quality conditions that may cause the malfunctioning of electronic devices in the grid [19].

Traction loads (trains) have both real and reactive power components [19] that change due to train movements such as acceleration, slowing and braking. These modes are illustrated in a typical daily load curve of the physical Wuhan-Guangzhou traction system in Figure 4.6(b). Active power consumption in the traction system is independent of the traffic density but depends on train movements, is mostly random and fluctuates as illustrated in Figure 4.7 [19].

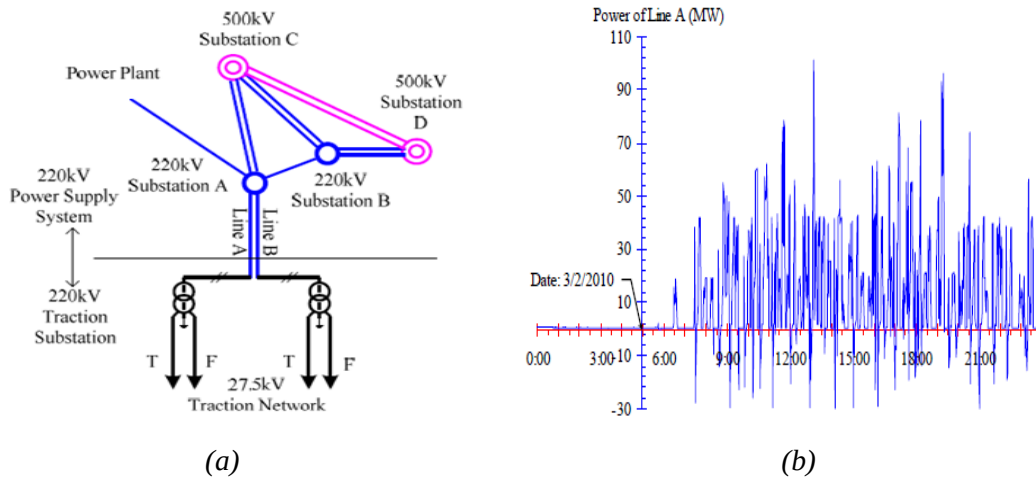


Figure 4.6: (a) Wuhan-Guangzhou supply system and (b) its typical daily load curve [19]

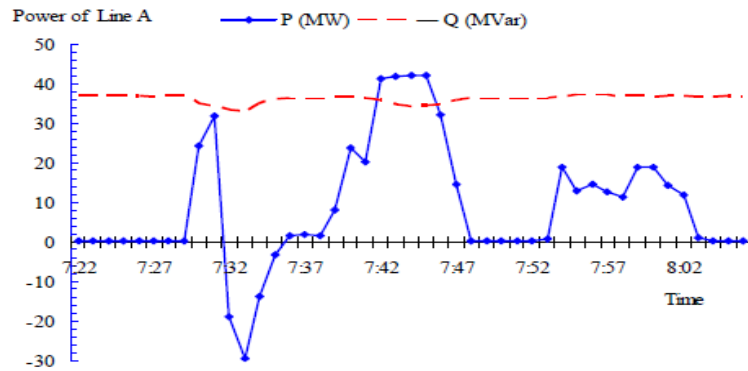


Figure 4.7: Typical load curve of the traction system [19]

The braking and regeneration of trains generate harmonic currents in the traction system [19, 21, 57]. These currents are random, unsteady, variable and distort current and fundamental voltage waveforms in the traction network and the power grid [4]. Utilities measure harmonics as the percentage of sites exceeding the voltage or current harmonic distortion limits. Voltage harmonics are quantified by the following expression [4]:

$$\text{THD}_v = \sqrt{\sum_{h=1}^N V_h^2} \dots\dots\dots (4.8)$$

THD_v is the total harmonic voltage distortion

N is the highest harmonic order considered in the calculation,

V_h is the RMS value of the h^{th} harmonic or the inter harmonic voltage component as a of percentage

This dynamic nature of traction networks and their power quality impacts complicates the performance of protective devices such as surge arresters. Thus, the presence of harmonics in the EGTN must be considered in surge arrester performance evaluations to assess their impact on surge arrester failures.

To curb poor power quality problems, the installation of multi-purpose balanced (MPB) transformers is preferred [63]. MPB transformers as shown in Figure A.3 (Appendix A) have the following distinct features [19], [63]:

- They provide symmetrical dual phase voltages of 27.5 kV (AC) for railway overhead lines to power electric trains,
- They supply three phase balanced voltages of 10.5 kV (AC) for railway substations and
- They have harmonic filters with improved power factor at reduced manufacturing cost.

Other transformers that reduce or eliminate negative sequence and zero sequence currents in the railway system are Scott, Le Blanc and Woodbridge transformers. However, these transformers have very low material utilization factors at 81.6%, 84.5% and 82.6% respectively [63]. There is no neutral point in the primary winding of the Scott and Le Blanc transformers therefore they require higher voltage insulation level for primary windings. Woodbridge transformers need two additional autotransformers for the two-phase railway traction power supply [63]. This makes these transformers expensive requiring long term operational needs and cost assessment before they are acquired.

Impedance matching (IM) transformers can also be utilized in addressing power quality problems and are common in Chinese traction networks. However, impedance matching transformers also have their drawbacks especially the increased cost of the harmonic filters. This is due to the high secondary voltages and the fact that the IM transformer does not provide a balanced three phase secondary voltage for use in railway substations [63]. Again, investment in these transformers requires long term operational benefit assessment as these transformers are expensive.

A monitor and limit approach seems sufficient in managing power quality problems in South African traction systems. For example, the splitting of MV busbars as shown in Figure 4.8 is a common practice in Eskom's traction network operation as this prevents mixing 'dirty' (traction loads) and "clean" (linear loads). Transformer tap changer overutilization causing carbon and other combustible gases building up in the diverter is prevented by periodically changing the feeding arrangement. This reduces tap changer maintenance, protects customer equipment from high voltage harmonics and ensures that operational objectives are met with least cost.

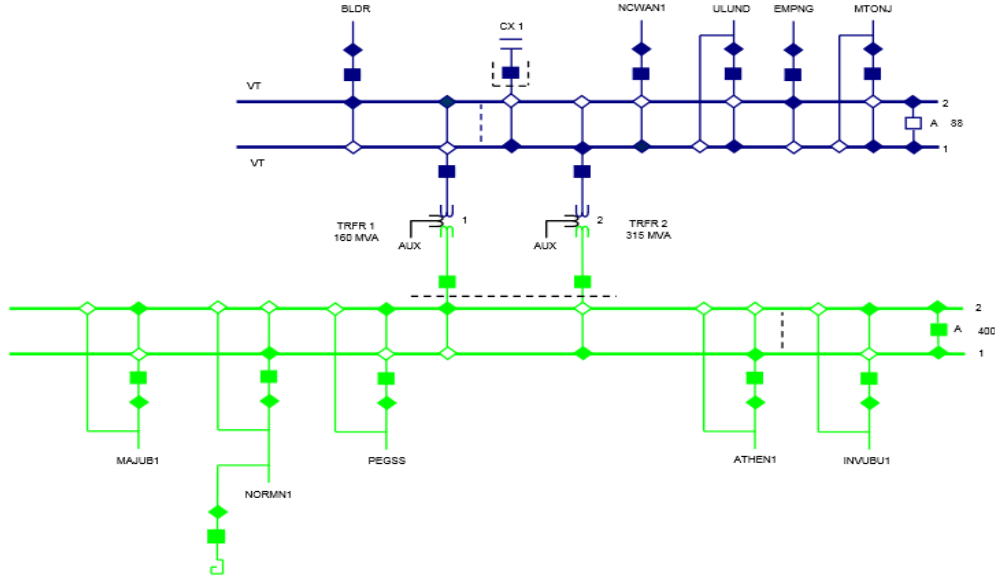


Figure 4:8: Umfolozi single line diagram showing the 88 kV busbar coupler A in an open position to split traction ('dirty') and non-traction ('clean') loads.

4.4 Evaluation of voltage regulation in traction systems

The voltage in the power network is regulated to protect equipment, personnel and animals. NRS 048 defines voltage regulation as the measure of the ability of the power system to control the steady state RMS voltage within $\pm 5\%$ limits [4], [58]. Voltage regulation measures the performance in sites exceeding the voltage limits during a 12-month moving period [5], and is expressed in [27] as follows:

$$VR \% = \frac{|V_{RNL}| - |V_{RFL}|}{|V_{RFL}|} \times 100 \quad \dots\dots\dots (4.9)$$

where:

VR % is the voltage regulation percentage

V_{RNL} is the no load RMS voltage

V_{RFL} is the full load RMS voltage

Voltage regulation limits in traction systems are the same as ordinary power networks. In the event that these limits are violated surge arresters in these networks may be susceptible to failures. It is therefore important to assess whether surge arresters that failed in the EGTN did so when the regulation limits were exceeded.

4.5 Traction load modelling

Traction network topologies and models are described in detail in [56], [24], [64]. These models are similar and take the form illustrated in Figure 4.9.

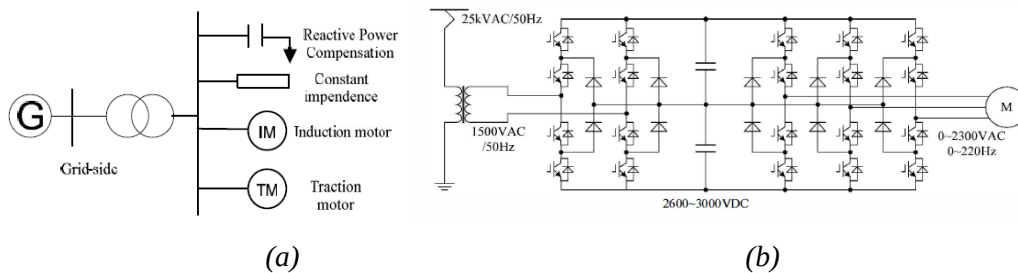


Figure 4:9: (a) model and (b) layout of the traction system [27]

The traction network in Figure 4.9(b) can also be represented as shown in Figure 4.10 where surge arresters would be positioned at positions A – C, B – A, and A – C. A complete electrical drawing of the power grid and a traction station is shown in Figure 4.11. Surge arresters at positions marked with x must withstand all voltage impulses from the grid or traction load

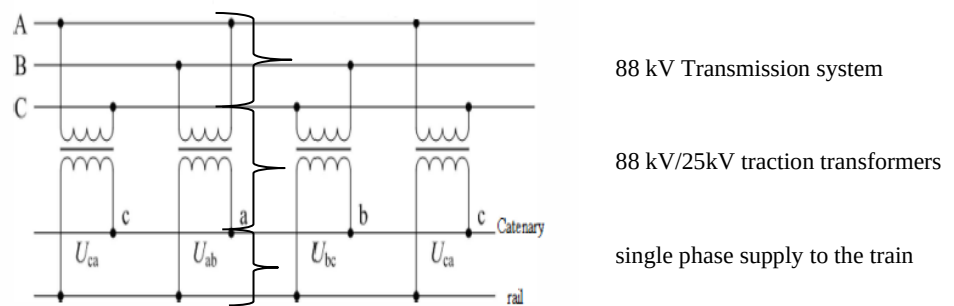


Figure 4.10: A detailed layout of a typical transmission line supplying a traction network [56]

Ideally, grid surge arresters should be matched with traction surge arresters to ensure that energy handing capabilities are met. Surge arresters that failed in the EGTN over the past ten years are located at the outgoing feeders from transmission substations. Customers indicated that their surge arresters did not fail during these incidents which suggest that the problem may be at transmission level.

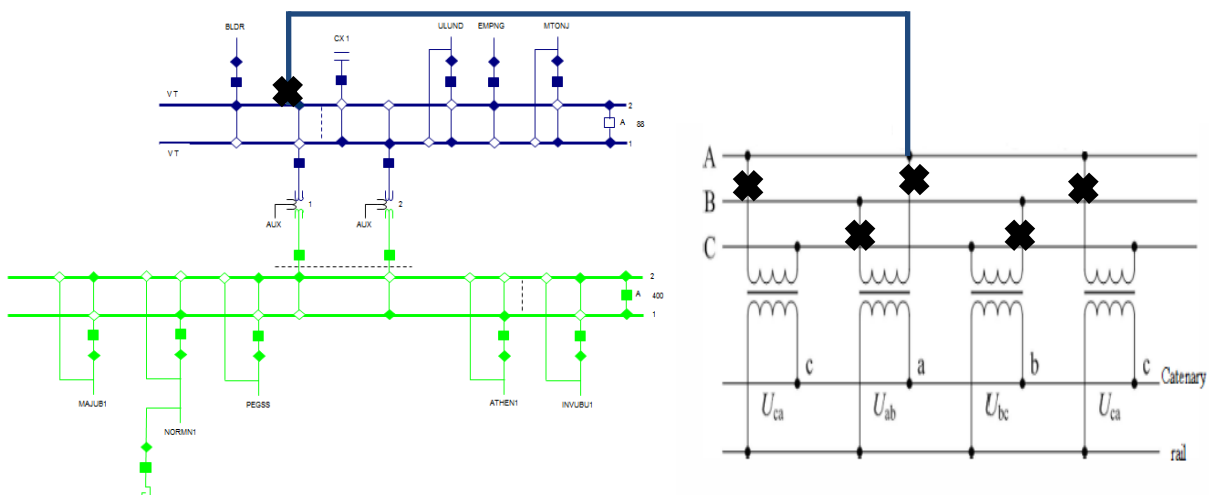


Figure 4.11: A complete diagram of a traction system with surge arresters' positions marked with X.

Chapter 5.

Design, operation, classification and selection of surge arresters

In this chapter the purpose of surge arresters, their designs, and operation during faulty conditions are discussed. The classification of surge arresters for selection and application purposes and the formulae used in computing important surge arrester parameters are also discussed. Voltage-current characteristics in evaluating surge arrester performance under transient conditions in the network are also highlighted. Important considerations in surge arrester modelling, parameter performance evaluations and suitability are made in this chapter to effectively evaluate simulation results.

5.1 Introduction

Power systems are designed to deliver power to customers with limited interruptions. Surge arresters protect supplies against voltage surges by diverting voltage surges to ground without tripping the supply circuit. Equipment vulnerability arises when surge arresters cannot direct voltage surges to ground. This condition occurs when surge magnitude(s) exceed surge arrester(s) voltage protective level(s).

The criticality of surge arresters is somewhat underestimated by many power engineers. Consequently, these devices are merely treated as part of other protective devices in the power system. However, other protective devices, for instance, shielding wires do not provide protection against voltage surges. These voltage surges may ultimately overstress a surge arrester and result in its failure, thus interrupting power supplies. Power system surge arresters must therefore be designed, modelled, and selected with caution. This requires an in-depth characterization and understanding of protected loads.

5.2 Basic surge arrester design principles

There are two fundamental principles that must be taken into consideration in the design of a surge arrester. *Firstly*, when the surge has dissipated, the arc in the surge arrester gap (whatever material it may be) should cease. Otherwise, if the arc is not extinguished, the current will continue to flow through the resistive path and the surge arrester may be destroyed. *Secondly*, the voltage drop across arrester terminals should not exceed the breakdown strength of the insulation of the equipment to be protected [12].

A typical surge arrester consists of a spark gap in series with a non-linear resistor and connected such that one end of the surge arrester is connected to the supply terminal of the equipment to be protected. The other end is connected to earth via the resistance, R as illustrated in Figure 5.1(a). The length of the gap is set such that the normal line voltage is not enough to cause an arc across the gap. If the arc is not extinguished, a dangerously high voltage develops across the arrester terminals leading to the breakdown of insulation [12].

There are several types of arresters that can be used in the power systems. These designs differ in constructional details. Common arrester types are rod, horn gap, multi gap, expulsion type, valve type and metal (Zinc) oxide gapless arresters (MOSAs) [12], [65].

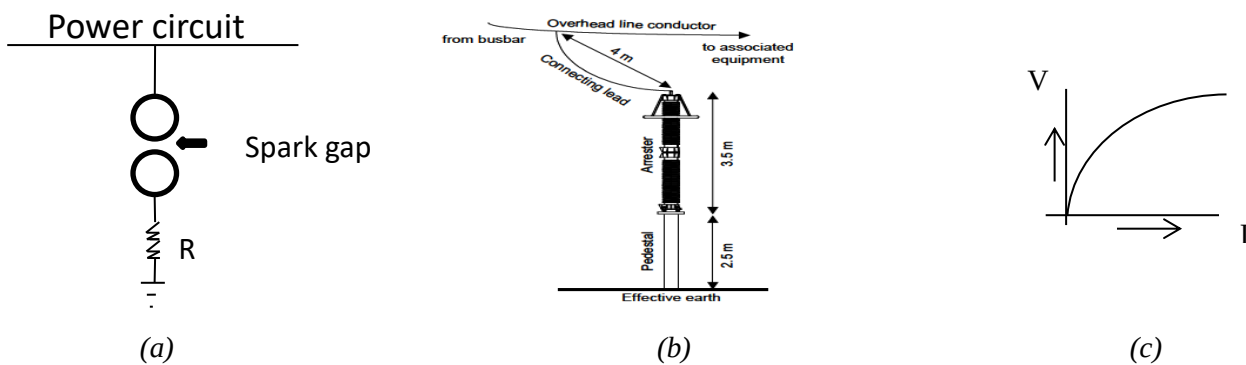


Figure 5.1: (a) The basic surge arrester design [12], (b) surge arrester application [66] and (c) V-I characteristic curve [12]

The design of MOSAs involves the insertion of metal oxide elements inside the porcelain or polymer housing. The polymer housing provides the exterior insulation and mechanical strength to the surge arrester. During construction, metal oxide elements are wrapped with glass fiber material and soaked with resin which makes the surge arrester rigid as shown in Figure 5.2(a).

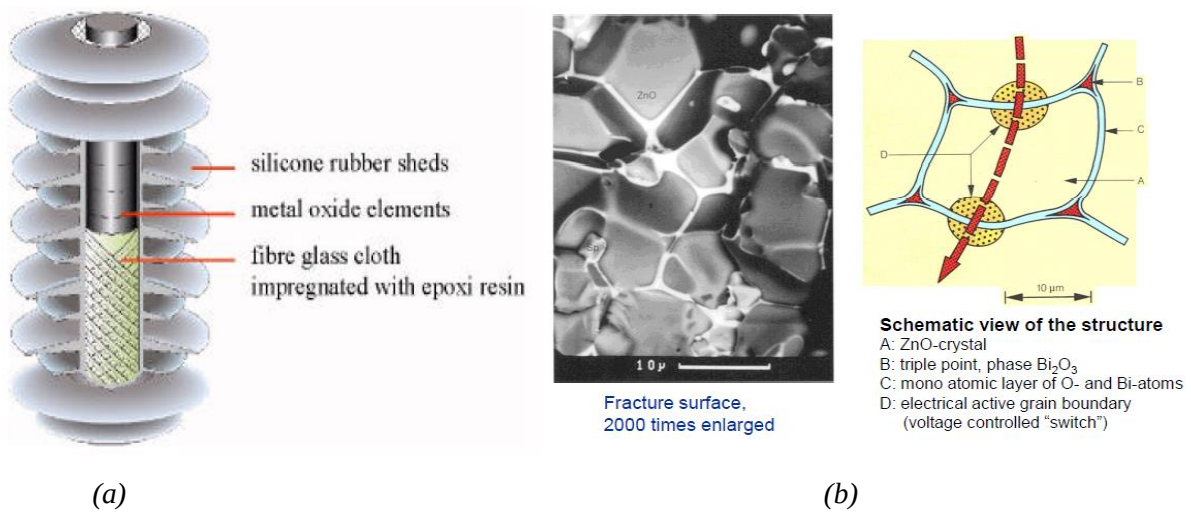


Figure 5.2: (a) Wrapped gapless MOSA [65]; (b) the molecular structure of the metal oxides [67]

Most manufacturers of metal oxide surge arresters follow the design and manufacturing practice described by [65] as illustrated in Figure 5.3.



Figure 5.3: The surge arrester manufacturing process [68]

5.3 Basic surge arrester operation principle

The basic principle of a surge arrester operation is described in [12] as follows: “(i) under normal operating conditions, for instance, when there is no surge on the line or any part of the network the surge arrester is ‘OFF’. This means there is no conduction of current to earth through the gap and the resistor, (ii) on occurrence of an overvoltage, the air insulation across the gap breaks down and an arc develops providing a low resistance path for the surge to ground. In this way, the excess charge on the line due to the surge is harmlessly conducted through the surge arrester to the ground instead of being sent back over the line and (iii) In the event that the surge is extinguished, the resistor (through its non –linearity property) provides a high resistance to make the gap non-conducting”.

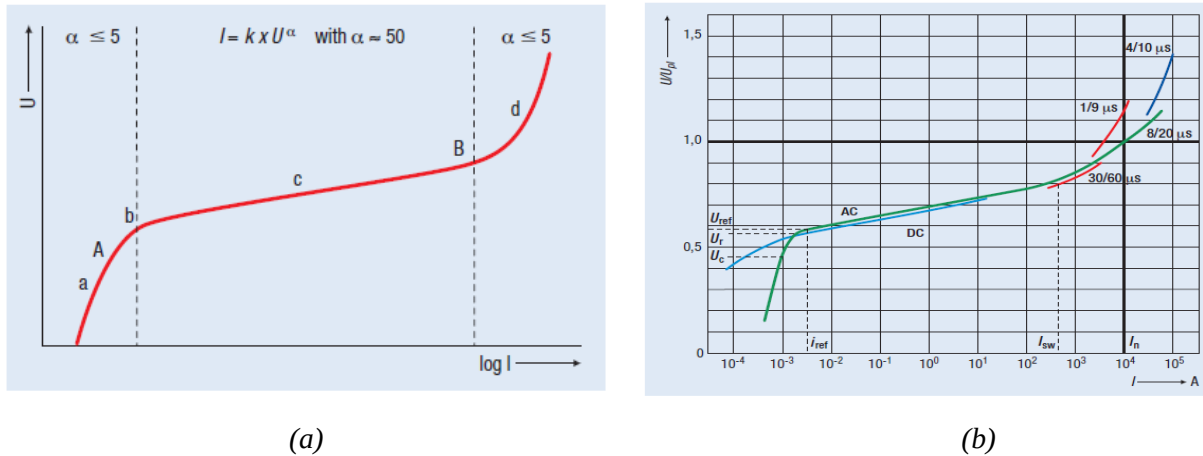


Figure 5.4: (a) V-I characteristic and parameters that define operation zones of MOSAs and (b) monitored parameters for performance evaluations of MOSAs [69]

MOSAs without gaps have improved non - linear characteristics as shown in Figure 5.4(a), hence they are popular and these have parameters indicated in Figure 5.4(b). These types of surge arresters are installed in the EGTN that supplies traction loads. The synthetic material in MOSAs is directly molded onto the metal oxide elements which have an extremely non-linear current voltage characteristic described by [69]:

$$I = kU^\alpha \dots\dots\dots (5.1)$$

Where:

$$5 \leq \alpha \leq 50,$$

α and k are parameters that define the current characteristic and

U is the lightning impulse voltage level

The relationship between this non-linear current (that flows in the metallic parts of the MOSA) and the voltage (lightning impulse) is illustrated in Figure 5.4. Points in the characteristic curve are: a – capacitive linear area where current is less than 1m; b – knee point which is a transition from insulating to conducting; c – strongly non-linear area; d – ohmic linear current area; A – area of continuous operating voltage, U_c ; and B – residual voltage U_{res} , protection area [57]. The polymer housing is made up of silicone or silicone rubber. This rubber is hydrophobic and elastic and has stable and high dielectric withstand strength. This makes the MOSA resistant and stable to water, high temperatures and tearing [69], [65].

MOSAs provide smooth voltage grading without flashovers. There is also no possibility of gases building up in these arresters. This is because the synthetic material is directly molded onto the metal oxide blocks. However, in humid areas, silicone becomes less rigid and they are made of different materials with different insulating properties. Therefore, these arresters are likely to fail under severe temporal overvoltage [69], [57].

The design of MOSAs entails the pressing together of metal oxide blocks between electrodes as shown in the manufacturing process in Figure 5.3. In the event of voltage increase at the arrester terminals, the current rises according to the characteristic curve shown in Figure 5.4(a). This must be continuous and without delay so that no flashovers occur. This is done such that the arrester skips to the next conducting condition. Once the overvoltage subsides, the current reduces, thus there are no spark gap currents but only leakage currents which are very small [69], [57]. Typical protective level and maximum follow through currents for different surge waveforms are shown in Figure 6.7(b).

5.4 Surge arrester types, classification and general applications

The first generation of surge arresters were rod gap arresters, horn gap arresters, multi gap arresters, expulsion type arresters and valve type arresters [12]. Towards the end of the 20th century, metal (Zinc) gapped surge arresters came into the market [12], [67].

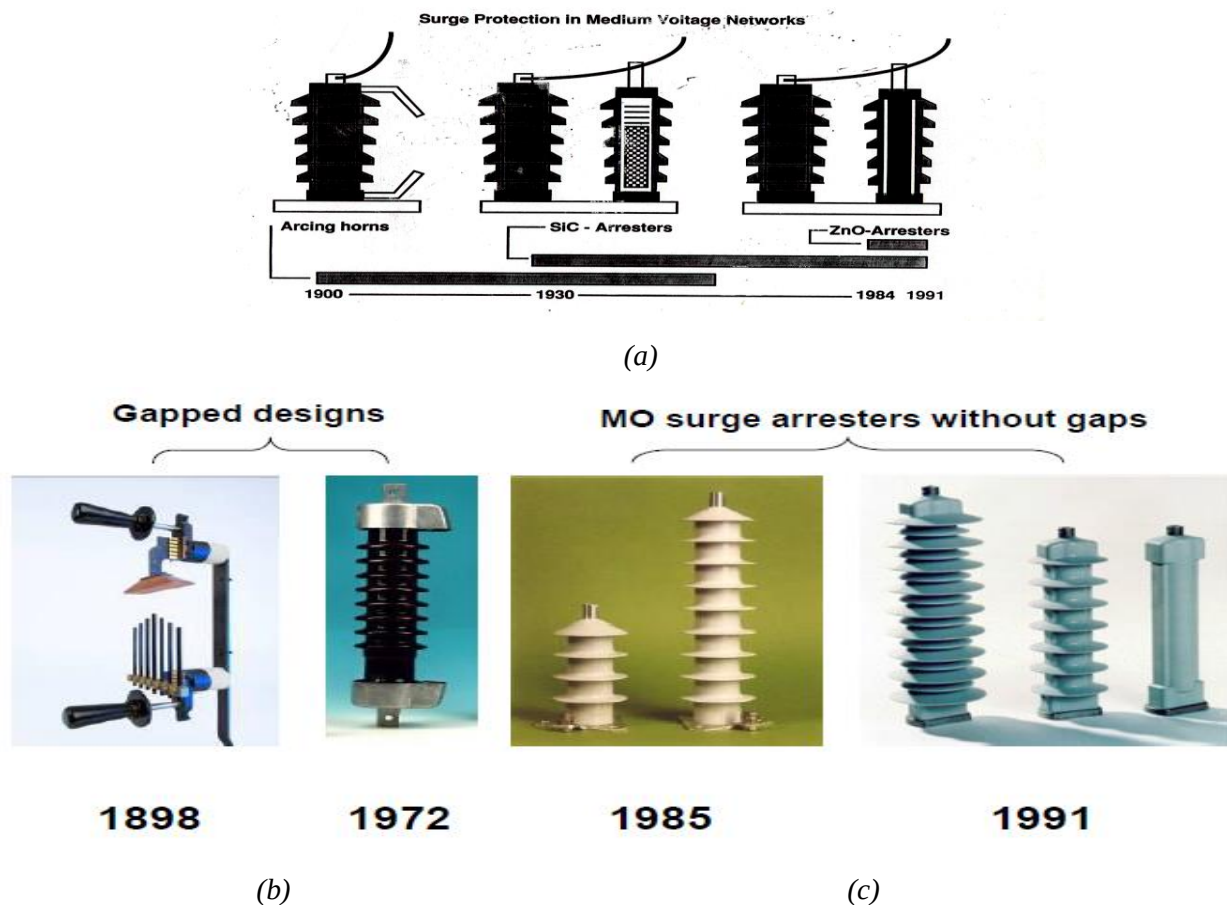


Figure 5.5: (a) The evolution of surge arresters [68], (b) surge arrester gap designs and (c) ungapped designs [67]

Over the years, these arresters have been optimized into metal oxide (ZnO) gapless surge arresters with different materials [67] as shown in Figure 5.5. Surge arresters in the EGTN are made up of metal (Zinc) oxide elements or stacked resistors that form a variable resistor, hence they are called metal oxide surge arresters. These surge arresters consist of resistive elements that can be either gapped or ungapped. Un-gapped MOSAs provide better V-I characteristics than gapped surge arresters. Ungapped MOSAs have low voltage drops and do not lead to the heating of the arrester housing [75]. Surge arresters installed in the EGTN are ungapped MOSAs as established by installation records and original equipment manuals.

5.5 Surge arrester classification and identification

Surge arresters that operate at voltages of up to 66 kV are classified as line type or distribution class surge arresters. Surge arresters used in systems operating on voltages from 220 kV and above are classified as station type or station class surge arresters [2]. The minimum information on a surge arrester nameplate should indicate (i) designation of arrester, (ii) continuous operating voltage, (iii) rated voltage, (iv) nominal discharge current, (v) rated short-circuit current in kA, (vi) manufacturer's name, (vii) identification of the assembling position of the arrester, (viii) year of manufacture, (ix) serial number, and if sufficient space is available, also repetitive transfer rating, Q_{rs} , and contaminated withstand level of the enclosure [2].

It is generally accepted that station class surge arresters have a high energy absorption capability than distribution or line surge arresters. Station class surge arresters are classified by (i) designation, (ii) nominal discharge current, (iii) switching impulse discharge current, (iv) repetitive charge transfer rating and (v)

thermal energy rating [2]. Distribution or line surge arresters are classified by (i) designation, (ii) nominal discharge current, (iii) repetitive charge transfer rating and (iv) thermal charge transfer rating [2].

Surge arrester identification and classification are denoted by ‘S’ and ‘D’ prefixes for different surge arrester designations and for different duty cycles. For instance, SH, SM and SL indicate station surge arresters with high, medium, and low duty cycles. Similarly, DH, DM and DL indicate distribution surge arresters with high, medium, and low duty cycles. However, these descriptions tend to be insufficient and create ambiguity because thermal ratings are not based on a single thermal energy rating as shown in Table 5.1 [2].

Table 5.1: The classification of surge arresters [2]

Arrester class	Station			Distribution		
Designation	SH	SM	SL	DH	DM	DL
Nominal discharge current	20 kA	10 kA	10 kA	10 kA	5 kA	2,5 kA
Switching impulse discharge current	2 kA	1 kA	0,5 kA	--	--	--
Repetitive charge transfer rating, Q_{rs} (C)	$\geq 2,5$	$\geq 1,6$	$\geq 1,0$	$\geq 0,4$	$\geq 0,2$	$\geq 0,1$
Thermal energy rating W_{th} (kJ/kV)	≥ 10	≥ 7	≥ 4	--	--	--
Thermal charge transfer rating Q_{th} (C)	--	--	--	$\geq 1,1$	$\geq 0,7$	$\geq 0,45$

According to IEC 60099-4 surge arrester requirements manufacturers do not have to specify thermal charge transfer rating for station class arresters. Switching impulse currents and thermal ratings also do not have to be specified for distribution or line surge arresters. This means that, for station class surge arresters, the thermal energy rating specification is at the manufacturer’s discretion. Similarly, the specification of the switching impulse discharge current and thermal energy ratings is at the manufacturer’s discretion.

In practice, very few manufacturers specify surge arrester thermal energy ratings or energy absorption capabilities. Most manufacturers only specify rated voltage, continuous voltage, nominal voltage, and class 1 or 2 etc. Manufacturers normally designate classes 1 to 4 for surge arresters with a nominal discharge current of 10 kA whilst classes 4 to 5 are designated for surge arresters with 20 kA discharge currents as shown in Figure 5.6. Also, there is an understanding that low classes have lower energy absorption capabilities whilst higher classes have higher energy capabilities. This leaves other parameters unknown especially when datasheets are not readily available, and replacements are to be done urgently after failures. Additionally, not having specific thermal energy ratings or energy absorption capabilities may lead to incorrect surge arrester identifications and selections.

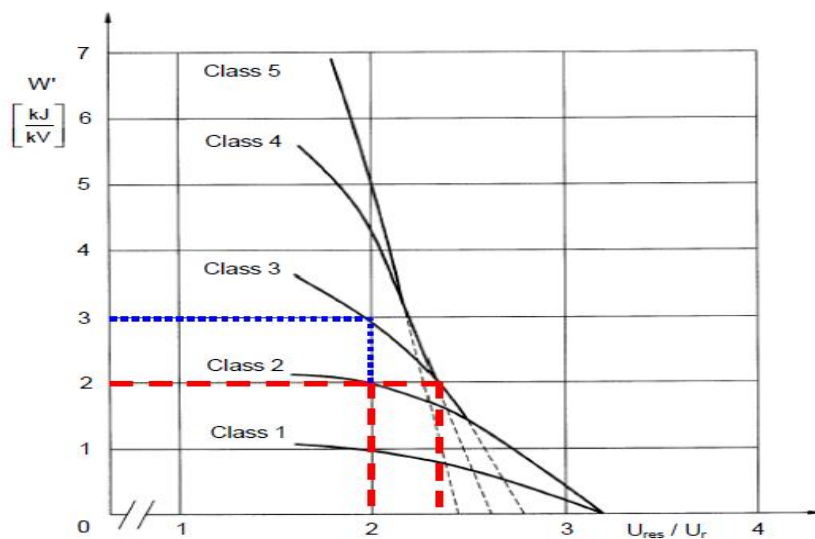


Figure 5.6: Different surge arrester classes with different energy ratings [66]

Eskom specifies classes 1 and 2 for distribution line surge arresters. Station surge arresters are specified for substation applications [2]. The thinking is that line surge arresters are subjected to less stresses in the distribution network hence do not require higher energy absorption capabilities. This is because several “T” offs and spurs exist in these networks. In substation applications, there is usually one outgoing feeder supplying large loads thus surge arresters with higher energy capabilities are required. However, it is not clear if this practice is adopted for surge arrester application feeding traction loads. This creates problems in identifying surge arresters that have failed in traction networks according to class. This also makes the selection of surge arresters for these networks difficult and may lead to incorrect surge arresters being installed in the network. Currently, Eskom has decided to install class surge arresters for new installations at substations and on transmission lines supplying traction networks.

5.6 Application of surge arresters

Gapless metal oxide surge arresters are widely used in power systems. The application of a surge arrester is based on its design parameters, V-I characteristic, and energy absorption capabilities under abnormal conditions such as overvoltages in the power system [12], [65]. The behavior of the network, surge arrester identification and selections are critical in surge arrester applications. This requires accurate modelling, analysis, and simulation of the network before the surge arresters are selected.

5.6.1 Different types of MOSAs and their applications

Power systems are exposed to overvoltages which might overstress the insulation of the equipment used [65]. The application of the surge arresters is such that line or busbar voltages are limited to values not overstressing the adjacent equipment to be protected as illustrated in Figure 5.7(a).

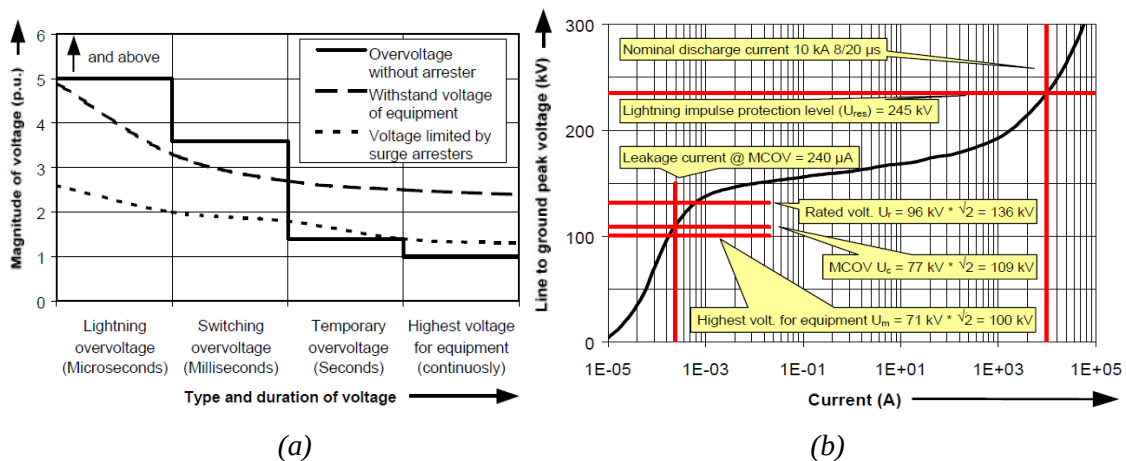


Figure 5.7: (a) Grading of different voltages for surge arrester applications and (b) example of 110 kV surge parameters that define its V-I characteristic [65]

There are four different types of metal oxide surge arresters that are widely used in power systems namely (i) porcelain, (ii) tube design polymer, (iii) wrapped design polymer and (iv) cage design polymer metal oxide surge arresters [65], [70].

Table 5.2: Different types of surge arresters with their mechanical properties [65].

Property	Design	Tube design	Cage design	Wrapped design
System voltage in kV		170	170	170
Static cantilever strength in kNm		14,7	2,8	0,8
Length in m		1,76	1,77	1,56
Headload in kN		8,4	1,6	0,5
Deflection in mm		44	173	n.a.

5.6.1.1 Porcelain housed metal oxide surge arresters

The insulation in MOSAs with porcelain housing is poor. These arresters are not hydrophobic in comparison to polymer housed arresters. They allow moisture ingress over time as they age [69], [71]. Porcelain MOSAs also shatter due to poor mechanical strength. These disadvantages have caused these types of arresters to be phased out by most utilities [65]. Eskom is also phasing out porcelain surge arresters and replacing these with polymer MOSAs.

5.6.1.2 Tube and cage design polymer metal oxide surge arresters

These arresters have polymer housing and offer greater mechanical strength as shown in Table 5.2. They can withstand large, short circuit currents. These surge arresters are common in mines as they are reliable and can also withstand seismic activity [65]. Surge arresters installed in the EGTN do not fall within this category.

5.6.2 Wrapped design metal oxide surge arresters

These arresters are simple to design with the utilization of fiber glass cloth that is impregnated and wrapped around metal oxide varistors. They are common in Eskom's transmission and distribution medium voltage systems. This is because they offer desired performance at a reasonable cost. This type of surge arrester design is studied in this research.

5.7 Energy absorption capabilities of a surge arrester

Power networks may experience temporal overvoltages due to faults. The duration of these overvoltages is between 0.1 seconds and several hours. Overvoltage magnitudes are usually not higher than $\sqrt{3}$ pu [57]. These overvoltages are dangerous for the system's operation and have adverse effects on equipment insulation [57].

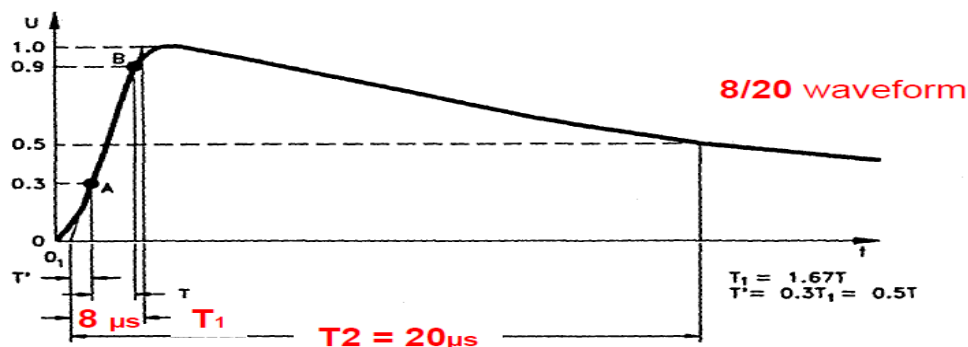


Figure 5.8: The standard lightning waveform as described in IEC 60-1

Lightning and switching overvoltages have a direct impact on a surge arrester's performance. These overvoltages are illustrated in Figure 5.8. The behavior of these overvoltages is studied by analyzing 8/20 waveforms which are standard IEC test signals for surge arrester performance evaluations. Lightning overvoltages are fast front wave overvoltages that reach peak values within a few microseconds. These surges decay quickly in comparison to switching overvoltages which are slow front overvoltages [57].

Switching surges occur during switching operations and consist mostly of heavily damped oscillations. These surges are at frequencies and magnitudes of several kilo Hertz and up to 3pu [57], [72]. Switching surges are rare but severe when they occur thus remaining a serious concern for power engineers. Overvoltage protection can be achieved in two ways: (i) avoiding lightning voltages at the point of origin. This is achieved by installing shielding wires in front of the substation that intercept lightning. (ii) limiting overvoltages near electrical equipment. This is achieved by installing surge arresters closer to the electrical equipment [57].

The former method appears to be less effective because of small distances between shielding wires and phase conductors. This is because direct lightning strikes on the shielding wires lead to immediate flashover to the line conductors. This condition causes induced overvoltages which cannot be avoided by shielding wires. The latter method is more effective as surge arresters provide sufficient protection against overvoltages in the vicinity of electrical equipment. Moreover, one can also easily pin point through inspections if a surge arrester has flashed to ground or failed. This requires condition monitoring such as infra-red scanning and current leakage tests. These tests assist in assessing the integrity of installed surge arresters. However, switching overvoltages are caused internally in the system and are random in nature. Therefore, the evaluation of surge arrester parameters at a planning state is paramount.

5.7.1 Evaluation of surge arrester energy absorption withstand capabilities

The most important surge arrester parameters are continuous operating voltage (U_c), rated voltage (U_r), rated discharge current, residual voltage (U_{res}), lightning impulse protection level, and energy absorption capability (EAC) [10].

These parameters are listed amongst various parameters in the IEC 60099-4 specification. The IEC surge arrester specification does not expressly define the energy capability of an arrester but only specifies station class surge arrester EAC limits [10]. The EAC of a surge arrester is explained by [73] where this parameter is expressed by the following equation:

$$E = \int_{t_0}^t U(t) I(t) dt \dots\dots\dots (5.2)$$

where:

$U(t)$ is the residual voltage of the arrester in kV and

$I(t)$ is the discharge current through the arrester in kA.

Most manufacturers compute energy absorption in kJ/kV (U_c)

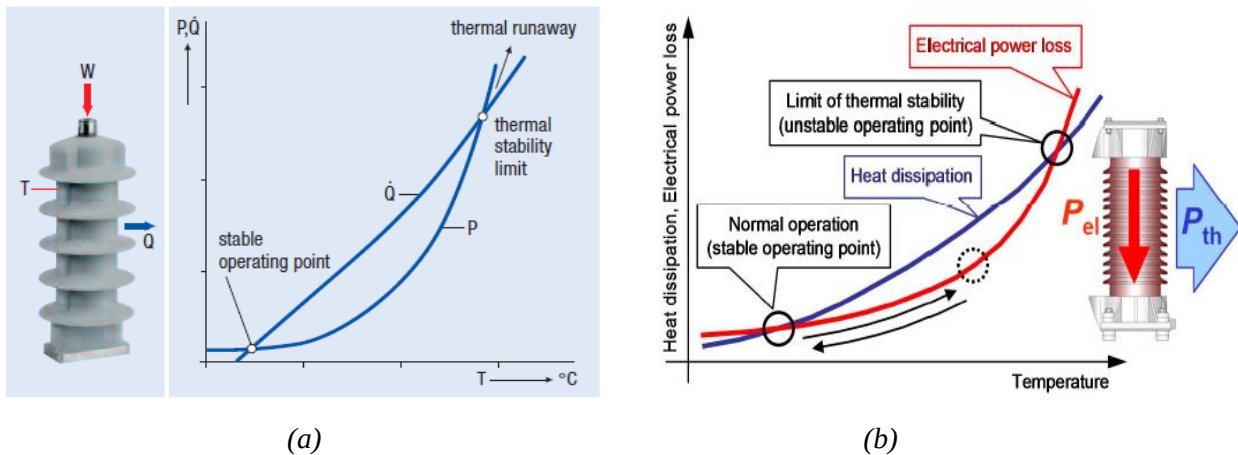


Figure 5:9: (a) Power losses in the MO blocks as heat flows to the exterior and (b) thermal stability limits [67]

If a surge arrester's energy absorption capability (EAC) is exceeded, the surge arrester will be destroyed [10]. Surge arrester thermal stability is considered critical to ensure that the surge arrester operates within designed

and intended conditions. This is illustrated in Figure 5.9(a) where real and reactive power losses in the arrester are evaluated against temperatures in MO blocks.

It can be observed in Figure 5.9(b) that as the heat builds up inside the metal block in the surge arrester the surge arrester performance becomes thermally unstable. This heat is dissipated through the surge arrester housing however, under abnormal conditions the arrester's thermal stability limit may be exceeded. The persistence of these conditions will destroy the surge arrester.

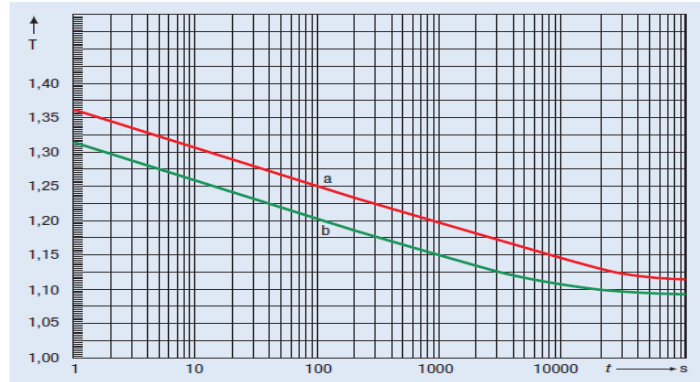


Figure 5.10: (a) ABB surge arrester EAC evaluation for pre-stress (curve a) and post-stress (curve b) conditions [69]

Manufacturers usually evaluate EAC limits to prove to customers that their surge arrester can withstand pre-stress and post-stress conditions. An example of this is shown in Figure 5.10. The temperature of the surge arrester (T) is calculated as a ratio of the temporal overvoltage, TOV and continuous operating voltage (U_c).

Table 5.3: ABB's technical data for different surge arrester classes [69]

Line discharge class IEC 60099-4	-/*	1	2	2	3	4	5
Nominal discharge current I_n in kA	5	10	10	10	10	20	20
High current impulse I_{hc} in kA	65	100	100	100	100	100	100
Switching impulse current I_{sw} in A	-/**	125 / 500	125 / 500	125 / 500	250 / 1000	500 / 2000	500 / 2000
Operating duty test, performed with	$1 \times I_{hc}$	$1 \times I_{hc}$	$2 \times I_{ld}$	$2 \times I_{ld}$	$2 \times I_{ld}$	$2 \times I_{ld}$	$2 \times I_{ld}$
W' in kJ/kV U_c	2.6	3.0	5.2	5.5	9.0	13.3	21.0
W'_{hc} in kJ/kV U_c	2.1	3.6	3.5	3.4	3.3	3.2	3.0
Rectangular wave I_{rw} , 2 ms in A	250	250	500	550	1000	1350	2700
Diameter of MO resistors in mm	38	38	42	47	62	75	108

The dimensioning of a MOSA is important for EAC evaluations and for selection purposes. An example of ABB surge arrester technical information is shown in Table 5.3. Utilities must verify this information by ensuring that manufacturers carry tests to prove that their surge arresters are adequate for a particular application. Surge arrester tests are carried out in laboratories with one source voltage connected across the surge arrester. Therefore, other practical conditions such as the nature of network where these surge arresters will be installed are not fully taken into consideration. This usually leads to utilities making ill-informed purchase decisions and inadequate specifications. This may be the case with the surge arresters that were selected and installed in the EGTN.

5.7.2 Computation of energy absorption capabilities in surge arresters for selection purposes

In practice, power engineers use energy equations and voltage-current characteristics curves to perform quick surge arrester calculations. This is done prior the selection of surge arresters to assess if a particular arrester meets application requirements. An example of the surge arrester calculation is illustrated in [73] as follows:

Given that the energy discharged by the surge arrester is:

$$E = V_a I_a t \dots\dots\dots (5.3)$$

where:

V_a is the arrester voltage and

I_a is the arrester current

The duration of the switching impulse can be estimated as the time for a surge to travel twice the length of the line (L), such that the time duration is expressed as:

$$t = \frac{2L}{c} \dots\dots\dots (5.4)$$

where,

c is the speed of light which is 300,000 km/s or 3×10^8 km/s

Suppose the line is charged to a switching surge level, V_{ss} , the surge is discharged through the line surge impedance into the arrester. If the arrester voltage is denoted by V_{arr} and the line surge impedance by Z_0 , then the equation relating these parameters can be expressed as:

$$V_{ss} = I Z_0 + V_{arr} \dots\dots\dots (5.5)$$

Where:

I is the surge current in Amperes (A). Re-arranging equation (5.5) yields:

$$V_{arr} = V_{ss} - I Z_0 \dots\dots\dots (5.6)$$

Equation (5.6) is a straight line with a negative slope and there exists an intersection between the straight line and the surge arrester voltage-current characteristic.

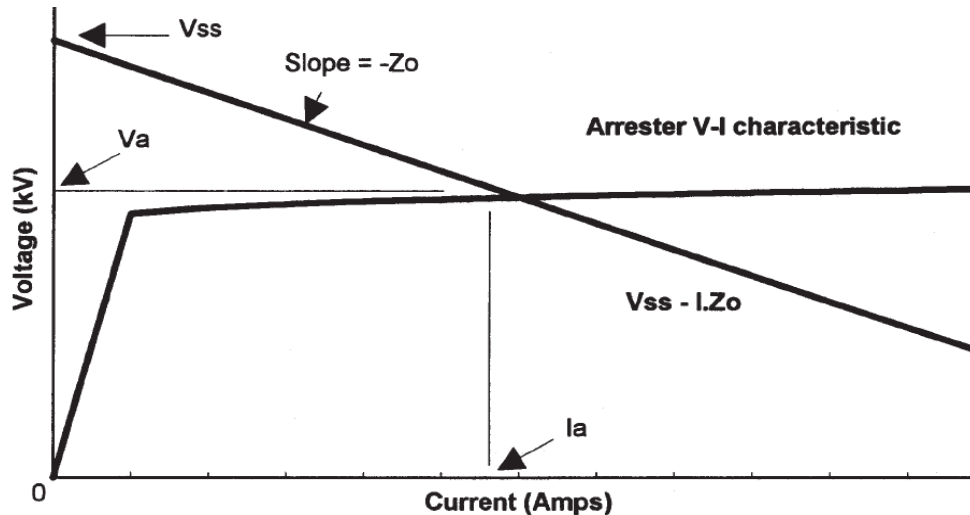


Figure 5.11: The graphical representation of the voltage-current characteristic and equation (7.5) [73]

This can be graphically illustrated as shown in Figure 5.11. Similarly, it is possible to construct families of curves for different surge arrester ratings, different switching surge levels, and different line surge impedances. Examples of different curves are shown in Figure 5.12 where maximum continuous voltages (MCOVs) are utilized in the calculation of energy absorption capabilities.

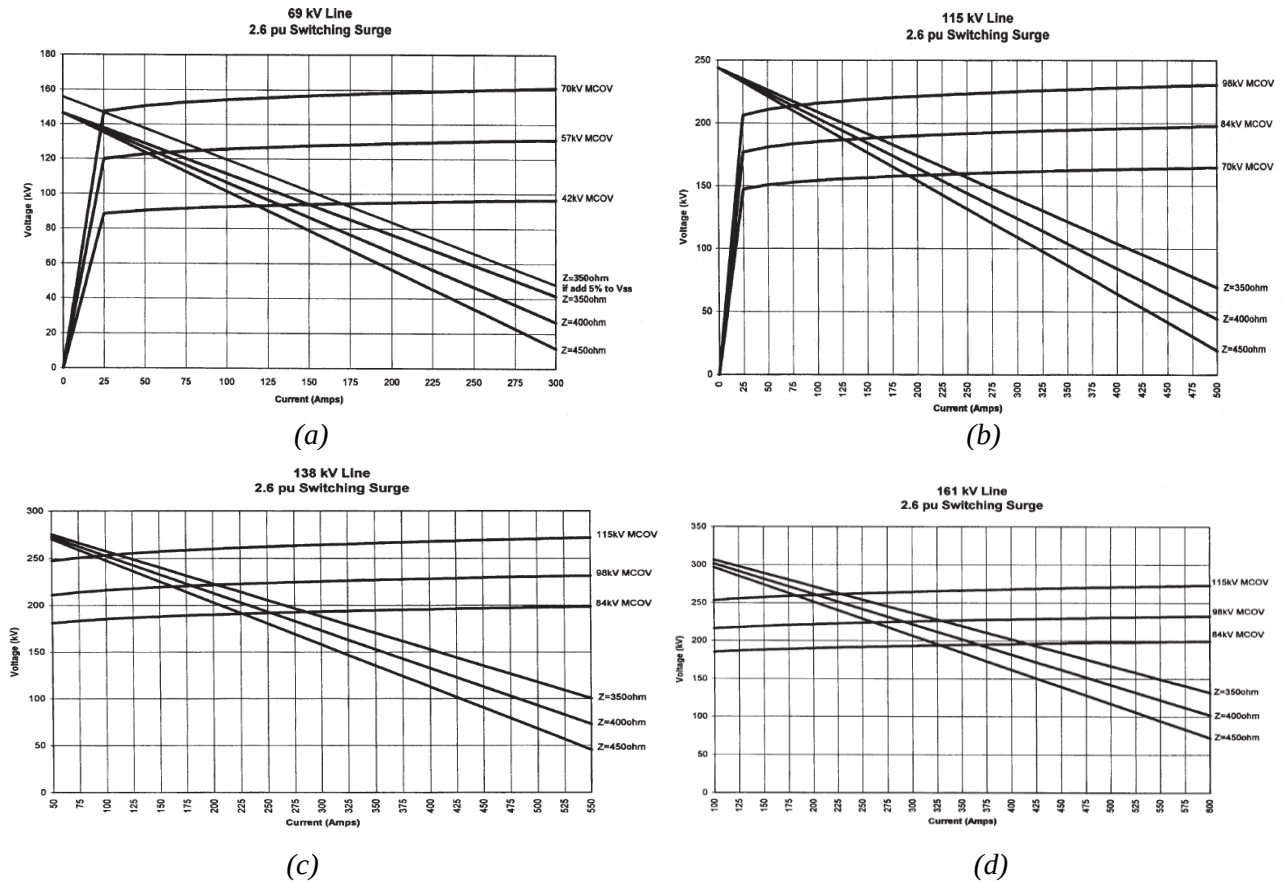


Figure 5.12: Surge arrester voltage – current characteristics with different line surge impedance and MCOV values [73]

It should be noted that a different per unit value would simply result in a proportional shift in the $V_{ss} - I Z_0$ curves in the direction of the y-axis. The example below illustrates the application of equations (5.3) to (5.6) in the computation of the EAC of an arrester. These equations are used together with characteristic curves under different line surge impedances (these are shown as different impedance values and plotted as straight lines in surge arrester voltage current characteristics).

Example: Calculate the energy absorbed by a surge arrester installed to protect a 138 kV line which is 322 km long with a surge impedance of 400 Ω .

Solution: From the 115 kV line surge arrester characteristics shown in Figure 5.12, the intersection of the curves occurs at the point ($I_a = 137.5$ A, $V_a = 190$ kV).

Using equation (5.4) above the surge duration is

$$t = \frac{2L}{c} = \frac{2 \times 322 \times 1000}{300,000 \times 1000} = 2.15 \text{ milliseconds}$$

Substituting equation (6.4) into equation (6.3) yields,

$$E = V_a I_a t = 190 \times 137.5 \times 2.5 \times 10^{-3} = 65.31 \text{ kJ}$$

Therefore, the energy absorbed by the 84 kV MCOV arrester is $65.31/84 = 0.78$ kJ/kV

Similarly, using the 138 kV curve we get the intersection point (250, 190), such that

$$E = V_a I_a t = 250 \times 190 \times 2.5 \times 10^{-3} = 118.75 \text{ kJ, therefore the energy absorbed by the 84 kV/MCOV arrester is 1.41 kJ/kV.}$$

This example shows that the energy absorbed by the arrester depends on its terminal voltage and the arrester's discharge current. It can also be observed that higher surge arrester V-I characteristic provide higher energy

ratings. Furthermore, the MCOV determines if the surge arrester will withstand a particular surge voltage. However, there are other concerning observations that can be made in this example: (i) it is assumed that the surge impedance of the network is 400 Ω which is problematic because the surge impedance of a power network is usually unknown (ii) the maximum continuous overvoltage, MCOV is utilized to assess the surge arrester's energy absorption capability. The surge arrester energy absorption capability, W' in Table 5.3 was evaluated using the surge arrester's continuous operating voltage (U_c) whereas the surge arrester's MCOV was used for energy absorption capability evaluation in [73]. This shows inconsistencies in surge arrester energy absorption capability evaluations.

Power system voltages are classified according to either IEEE or IEC system voltage standards. Eskom system voltage classifications are based on IEC standards, thus U_c values are expected to be used in evaluating surge arrester energy absorption capabilities. Notably, [74] specifies an EAC value of 3.4 kJ per MCOV or U_c for 88 kV surge arresters. This treats the MCOV and U_c as same quantities, bringing confusion on whether these parameters are the same.

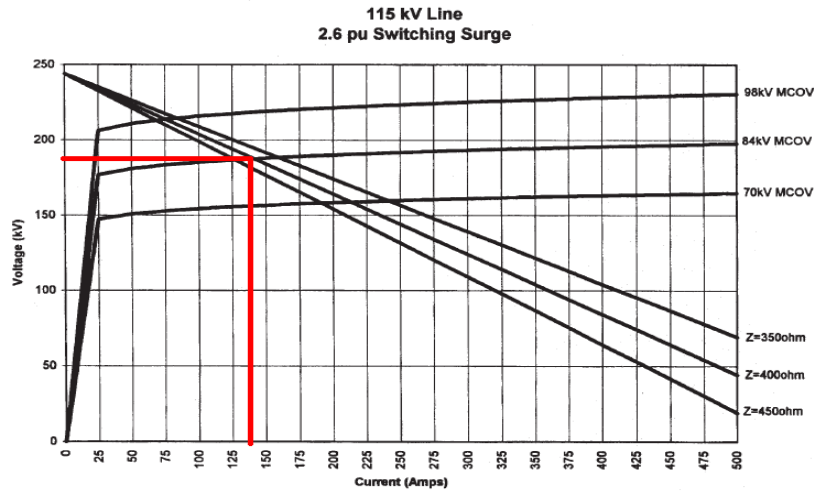


Figure 5.13: The point (137.5, 190) on the 115 kV characteristic curve

These ambiguities may lead to incorrect specification of energy absorption withstand capabilities. IEEE classified systems use MCOV values whilst IEC classified systems use U_c values as shown by [11] in Table A.2. MCOV and U_c parameters depend on earthing arrangements and line surge impedances as shown in Table 5.4 and Figure 5.14. These parameters also depend on the voltage regulation, v_r of the system. The U_c parameter of a surge arrester in an IEC classified system is computed in [75] as follows:

$$U_c = \frac{U}{\sqrt{3}} v_r \dots\dots\dots (5.7)$$

where:

U is the system nominal voltage of an IEC classified system,

v_r is the voltage regulation of the system

Similarly, the U_c parameter of a surge arrester in an IEEE classified system is computed in [75] as:

$$\text{MCOV} = \frac{U}{\sqrt{3}} v_r \dots\dots\dots (5.8)$$

Where:

U is the system nominal voltage of an IEEE classified system,

v_r is the voltage regulation of the system

Utilizing equations (5.7) and (5.8) in computing surge arrester EACs implies that a 138 kV line connected to power network that has a voltage regulation of $\pm 5\%$ will have a MCOV of 84 kV ($138\text{kV} \times 1.05/\sqrt{3}$). Similarly, the U_c parameter of an 88 kV surge arrester in the EGTN will be 54 kV ($88\text{kV} \times 1.05/\sqrt{3}$).

The MCOV of an 88 kV surge arrester was specified as 56 kV in [74], indicating that a $\pm 10\%$ was used. This is not in agreement with Eskom's voltage regulation limits [42] and [33]. This error is expected as the 88 kV line that feeds a distribution substation is the same line that leaves a transmission substation. However, the transformer tapping range at these substations is not the same as the transmission and distribution networks are regulated to within $\pm 5\%$ and 10% of nominal voltages, respectively.

The differences in system voltage classifications and errors in the utility specifications lead to incorrect surge arresters being designed by manufacturers. This in turn leads to inadequate surge parameter evaluations resulting in incorrect surge arrester selections. This is quite problematic for surge arresters that are to be applied in traction networks as these networks are very dynamic. This is because surge arresters to be installed in these networks require precise parameters to be specified to prevent failures.

Other manufacturers evaluate the energy absorption capability of a surge arrester in terms of the surge arrester's rated voltage i.e. kJ/kV (U_r). The rated voltage, U_r of a surge arrester in an IEC classified system is computed in [75] as follows:

$$U_r = \gamma U_c \dots\dots\dots (5.9)$$

Where:

γ is the system ground factor

Ground factors (shown in Table 5.4) depend on system earthing arrangements [3, 11] shown in Figure 5.14 with surge arrester positions as metal oxide varistor (MOV) blocks. U_r is a surge arrester parameter that ensures that overvoltages are directed to ground during faults or system voltage surges hence this is an important parameter.

Table 5.4: ABB's technical data for different surge arrester classes [69]

Type of System	Ground Fault Factor
Solidly Grounded 4 wire systems	1.25
Uni-grounded 3 wire systems	1.4
Impedance grounded systems	1.73
Isolated Ground Systems and Delta Systems	1.73

As indicated in equation (5.9), this parameter depends on MCOV or U_c parameters depending on the system voltage classification. Using equation (5.9), the U_r parameter of an 88 kV surge arrester in an effectively grounded system in the EGTN is 67 kV ($88 \text{ kV} \times 1.05/\sqrt{3}$) $\times 1.25$. Similarly, the U_r parameter of an 110 kV surge arrester in an effectively grounded system in United States of America is 84 kV ($110 \text{ kV} \times 1.05/\sqrt{3}$) $\times 1.25$.

Again, if MCOV or U_c surge arrester parameters are incorrectly used and no attention is paid to system voltage classifications, U_r parameters will also be incorrect. Eskom does not specify the U_r surge arrester parameter in surge arrester specifications in [74]. These uncertainties and inconsistencies could also be the cause of surge arrester failures in the EGTN. This is because MCOV or U_c and/or U_r parameters ultimately determine the energy absorption capabilities of a surge arrester. This makes the surge arrester energy absorption capability the single most important parameter in surge arrester performance evaluation and selection.

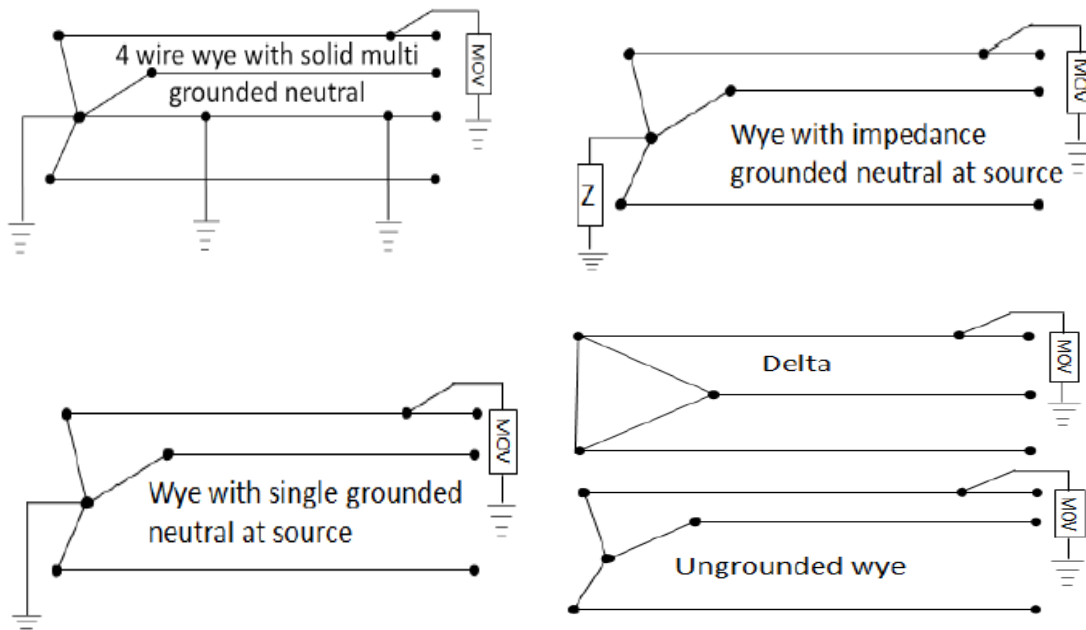


Figure 5:14: Utilization of metal oxide varistor surge arresters in different power system earthing configurations [11]

5.8 In-service factors impacting surge arrester performance

There are many possible causes of surge arrester failures in power systems. Common surge arrester failure causes are noted and classified in [68] as shown in Figure 5.15. Moisture ingress is the leading cause of failures of surge arresters. However, surge arresters may also fail due to different voltage conditions and other exterior factors. This is because when surge arresters are in service, they are exposed to stress voltages. These voltages originate from network and environmental conditions [35], [25]. In the case of MOSAs, these conditions can accelerate the ageing of their metal blocks and ultimately lead to their failures [35].

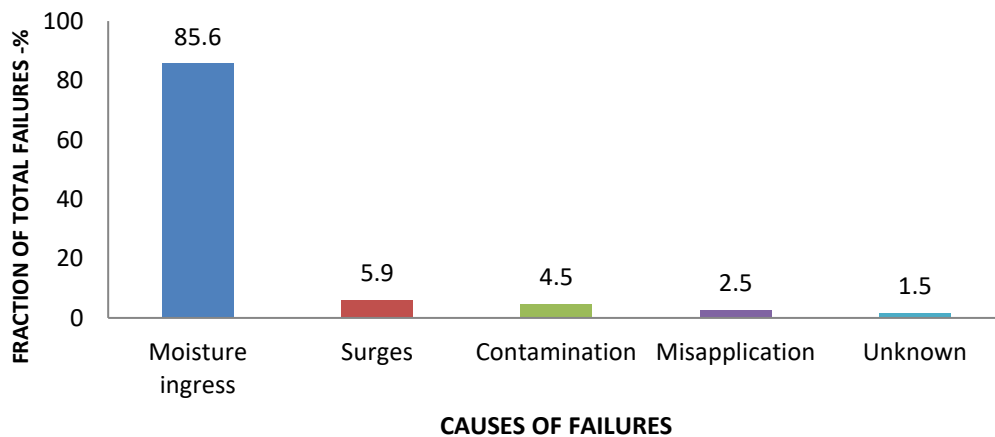


Figure 5:15: Ranking of common surge arrester failures causes [68]

5.8.1 Causes of in-service surge arrester deterioration

Main categories of degradation in surge arresters are degradation of the insulation properties and degradation of the protective characteristics [68].

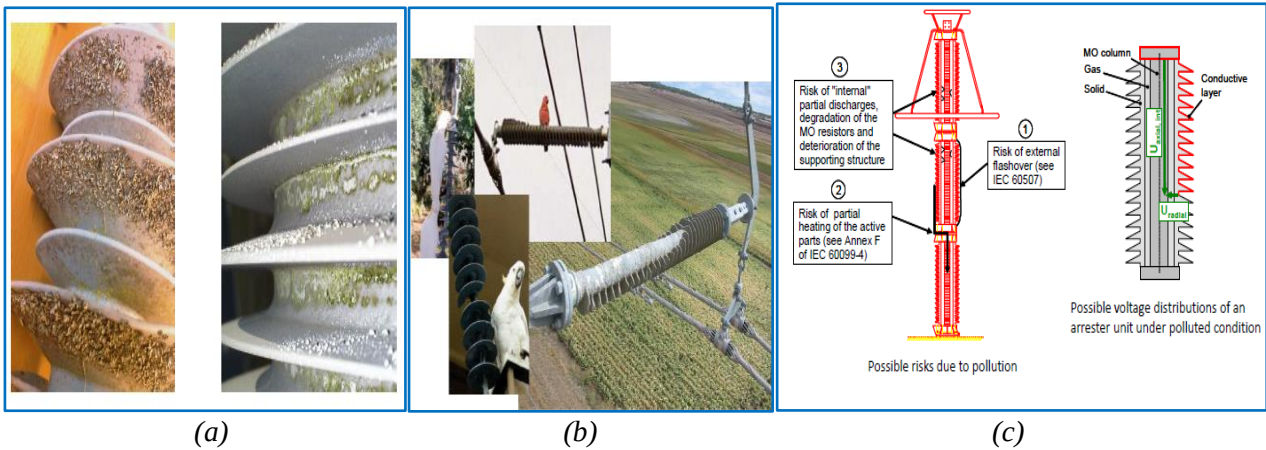


Figure 5.16: (a) The deterioration of the surge arrester polymer housing due to plant growth; (b) bird activity; (c) effects on the internal parts (right) [67]

The former is caused by the degradation of the surge arrester housing as shown in Figure 5.16(a). The latter is caused by the deterioration of internal parts such as metal oxide blocks as shown in Figure 5.16(b). MOSAs are filled with air, nitrogen, or gas under normal conditions. Initially, the gas humidity is low but the humidity inside the arrester increases over the years [67], [76]. This is due to the deterioration of the sealing and moisture formation on the varistor column causing an internal flashover [35], [67], [76] as shown in Figure 5.16(c).

There are many factors that can lead to the degradation of MOSAs shown in Figure 5.17 namely, sealing defects leading to ingress of moisture, discharges due to surface contamination, overloading due to temporary and transient overvoltages, long term ageing during normal service voltages, and internal partial discharge exceedances [25].

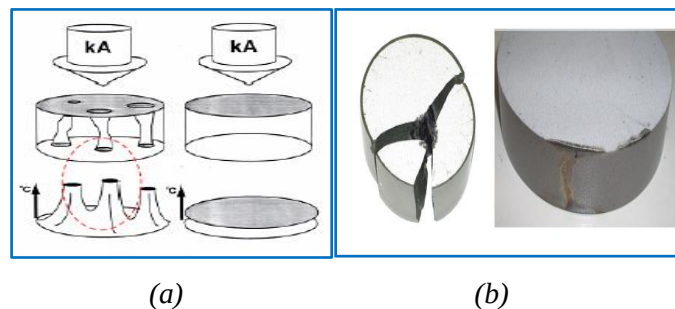


Figure 5.17: (a) The alteration of metal block homogeneity and (b) eventual damage of metal MO elements [68, 67]

Corona activity leads to electromagnetic disturbances resulting in partial discharges on the surface of the metal oxide blocks [76] as shown in Figure 5.18 (a). The degradation of the protective characteristic in the MOSA is caused by an increase in the resistive component of the continuous leakage current flowing through the arrester over time [25] as shown in Figures 5.18(a) and (b).

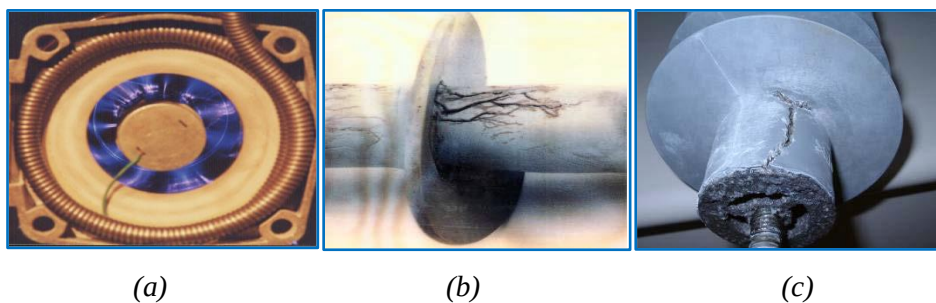


Figure 5.18: Intensive partial discharges (left) [76] and tracking due to electromagnetic activities [68]

The in-service conditions in Figure 5.18 have significant adverse impacts in surge arrester failures. These conditions must be considered in the surge arrester failure evaluations. It is possible that failures of surge arresters in the EGTN could have been caused by some of these conditions.

5.8.2 Modes of surge arrester failures

Surge arresters can fail in different modes and these modes of failures signal the underlying root cause(s) of failures. Surge arrester shattering, internal flashover and overloading are common modes of failures [76].

5.8.3 Shattering of the surge arrester housing

A surge arrester can fail due to its housing shattering; for instance, an arrester with porcelain housing may explode. This mode of failure is shown in Figure 5.19(a) and can cause severe damages to nearby equipment and pose a safety hazard to personnel. In cases of arresters with polymer housing, the housing may burst open, but the risk of housing material being scattered is more limited [76].

5.8.4 Internal flashovers

This mode of failure occurs when internal earth faults due to internal flashovers occur inside the arrester. These are generally difficult to detect.

5.8.5 Overloading

Surge arrester overloading reduces protection against overvoltages. Transient overvoltages, multiple lightning strikes and high-energy temporary overvoltages suppress an arrester's capabilities. These failures occur when an arrester has failed prior to a voltage surge. The degradation of metal oxide resistors can be caused by the deterioration of the insulating medium. This is inside the surge arrester housing and walls and usually caused by moisture. This moisture is in the form of vapor or water and elevates stresses inside the surge arrester [76].

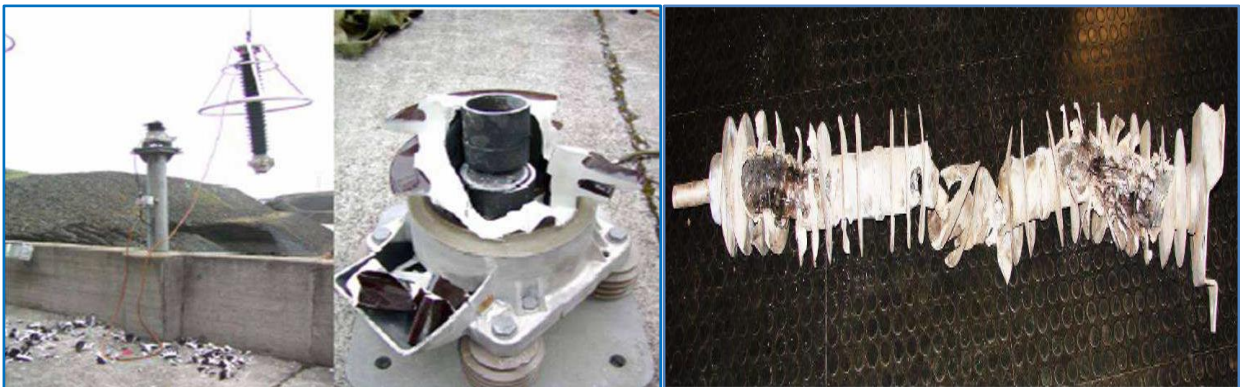


Figure 5.19: (a) MOSA with porcelain housing that failed catastrophically while in service [25]; (b) a faulted 88 kV surge arrester from the EGTN

Chapter 6.

Reliability evaluation of the EGTN

In this chapter, the reliability of the EGTN is evaluated *firstly* by representing the network in the RBTS format utilizing the FMEA and computing common reliability indices. *Secondly*, the MATLAB simulation code proposed by Shavuka et al. [1] is modified and applied in the EGTN and common reliability indices are computed. To assess the suitability of this code, results are compared with those computed from the FMEA method. The reliability indices used in Eskom's distribution and transmission divisions are also computed and compared with the MATLAB code and FMEA method. This is done by making certain observations in these indices to investigate a potential for the standardization of the reliability assessments in these divisions.

6.1 Introduction

Analytical methods provide accurate reliability evaluation of the power system [16]. However, the analytical method may be time consuming for large networks. In this case, the simulation method (SMt) is useful. FMEA method is used in the analytical method. In this method, the EGTN is drawn in the manner that allows FMEA evaluation as shown in Figure 6.1. In the simulation method, the MATLAB code compiled by Shavuka et al. [1] is edited and expanded to model the EGTN. Results from each method are compared for analysis.

6.2 Representation of the EGTN for reliability evaluation using the analytical method

EGTN comprises of three main transmission substations namely Umfolozi, Bloedrivier and Normandie substations that feed traction loads i.e. Spoornet or Transnet. A full single line of the EGTN is shown in Figure 6.1.

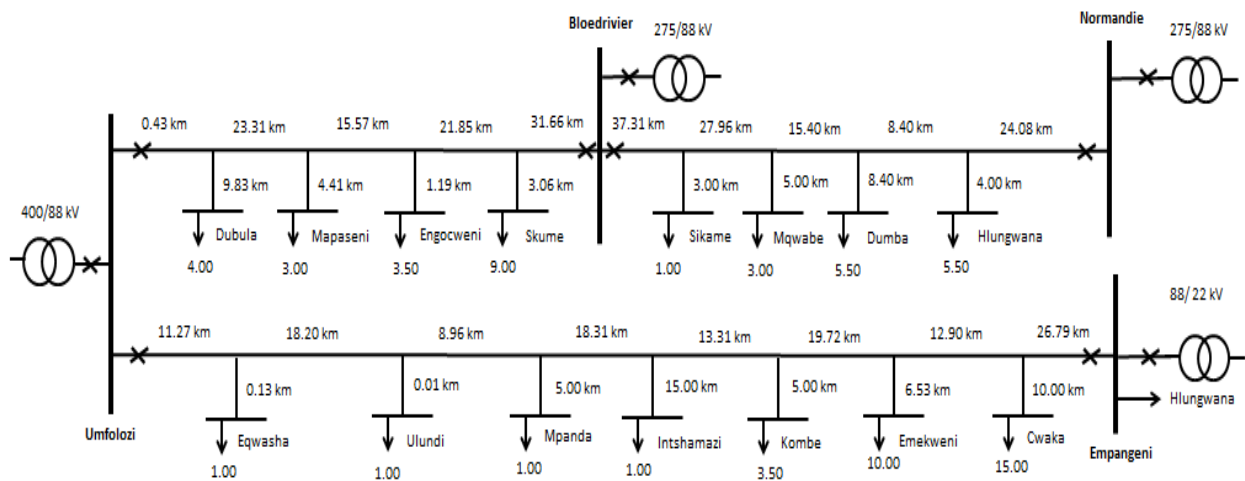


Figure 6.1: East Grid Traction Network single line diagram in MVA

The evaluation of reliability indices of a network is done by representing it in a Roy Billinton Test System (RBTS) format as shown in [16], [45]. EGTN's representation in RBTS format is shown in Figure 6.2. A feeder failure rate of 0.065 failures/year-km and transformer failure rate of 0.015 failures per year are utilized in the computation of reliability indices in the EGTN as advised in [45].

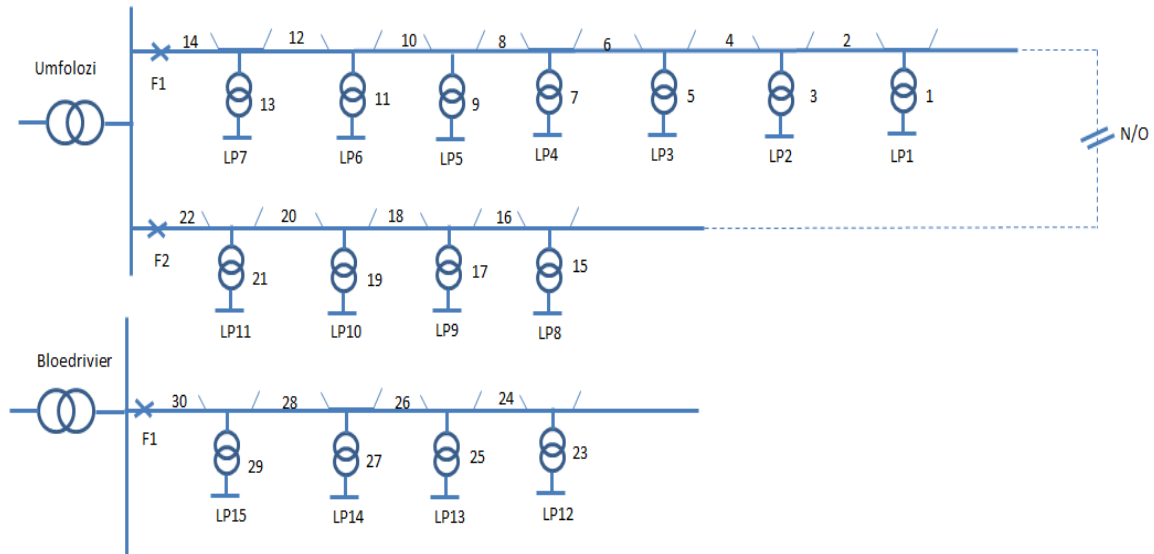


Figure 6:2: East Grid Traction Network single line diagram in RBTS format

A restoration time (r) of one (1) hour is used in calculating reliability indices. This is in accordance with East Grid emergency preparedness plans. This is the time taken to restore failed equipment on the lateral. A restoration time of five (5) hours is utilized for equipment on the backbone. Table A.9 shows the data used in the computation of reliability indices of the EGTN. There is a normally open point (N/O) between Umfolozi and Bloedrivier substations as shown in Figure 6.2. This normally open point is utilized to ensure continuity of supplies. This point is also used for fault finding on the Umfolozi – Bloedrivier 88 kV line in the EGTN.

6.3 Computation and comparison of the EGTN's reliability indices

Reliability indices namely SAIFI, SAIDI, CAIDI, ASAI, ASUI, ENS and AENS were computed in this network for reliability evaluation. It was noted in [5] and [33] that at Eskom, distribution and transmission that different reliability indices are used to assess these networks with different meanings. Therefore, reliability indices in this section are discussed in terms of distribution and transmission divisional appraisal methodologies. Systems Minutes in this study are calculated based on the 2015/16 annual system peak value of 33 722 MW.

6.3.1 Evaluation of Umfolozi 88 kV feeder 1 reliability indices

Reliability indices for this feeder were computed using FMEA and SMt. The results are shown in Table B.1. Each reliability index is discussed in terms of its interpretation in Eskom distribution and transmission divisions. Results are compared by assessing percentage differences as shown in Table B.1.

6.3.1.1 Observations made on the SAIFI of Umfolozi 88 kV feeder 1

- This feeder experiences about seven (7) hours of supply interruptions per year as observed in FMEA and simulation calculations.
- The difference in the SAIFI indices from both reliability evaluation methods is within +/-10%.
- SAIFI values from both methods are within Eskom's distribution SAIFI target of 20.22 hours of the 2015/16 financial year. This target was shown in Table 3.4.
- In transmission, SAIFI appears equivalent to the number of supply interruptions (NOI) which is seven for the 2016/17 financial year as expected. NOI was shown in Table 3.3.

6.3.1.2 Observations made on the SAIDI of Umfolozi 88 kV feeder 1

- This feeder experiences about twenty (22) hours of interruption per year as observed in FMEA and simulation.
- SAIDI indices from both methods are comparable as the differences are within $\pm 3\%$.
- The SAIDI of this feeder is within the SAIDI target value of 30.89 hours in Eskom's distribution appraisal as shown in Table B.1.
- Transmission Systems Minutes for this contingency is 0.1516 SM. This is within the 0.83 SM target shown in Table 3.3.
- SAIDI and SM indices appear to be similar. However, this relationship was not substantially studied in this dissertation.

6.3.1.3 Observations made on the CAIDI of Umfolozi 88 kV feeder 1

- Customers on this feeder experience about three (3) hours of sustained interruptions on average in a year. CAIDI indices from both reliability evaluation methods are within $\pm 10\%$.
- Since this index is the ratio of SAIFI and SAIDI indices, it is not exclusively appraised in Eskom's distribution performance plans.
- There is no specific index in Eskom's transmission that this index can be compared as evident in Table 3.3.

6.3.1.4 Observations made on the ASAI of Umfolozi 88 kV feeder 1

- This feeder is available for customers approximately 99.7% of the time in a year.
- FMEA and SMt methods yield similar results for this index.
- This index appears equivalent to the Eskom's transmission circuit availability index in Table 3.3.

6.3.1.5 Observations made on ASUI of Umfolozi 88 kV feeder 1

- This feeder is unavailable for about 0.3% of the time in a year.
- ASUI indices from both reliability methods are comparable.
- ASUI appears equivalent to the circuit unavailability index in Table 3.3.

6.3.1.6 Observations made on the ENS and AENS of Umfolozi 88 kV feeder 1

- ENS index shows that an outage on this feeder causes high energy losses. This has adverse consequences for Eskom's revenue. This is a concern as Transnet is a large power user.
- Transnet is on Transflex 1 tariff (this is about 68c/kWh) as shown in Table C.1. This equates to a R696,000 loss/year to Eskom when this feeder is on outage.
- Transnet also losses a lot of money when trains are stuck on the rails with adverse impacts on the economy of the Country. NERSA may also impose penalties and withhold incentives hence this index is critical for Eskom.
- ENS index computed by the two reliability evaluation methods is within $\pm 1\%$.

6.3.2 Evaluation of Umfolozi 88 kV feeder 2 reliability indices

Reliability indices for this feeder are shown in Table B.2 and these results are compared.

6.3.2.1 Observations made on the SAIFI of Umfolozi 88 kV feeder 2

This feeder experiences about four (4) hours of supply interruptions per year as observed in FMEA.

- SAIFI indices for this feeder using both reliability methods are within the $\pm 3\%$. These indices are also within Eskom's distribution's SAIFI target of 20.22 hours of the 2015/16 financial year shown in Table 3.4.
- Again, Eskom's distribution SAIFI appears equivalent to Eskom's transmission number of supply interruptions (NOI) which is seven (7) for the 2016/17 financial year as shown in Table 3.3.

6.3.2.2 Observations made on the SAIDI of Umfolozi 88 kV feeder 2

- This feeder experiences about sixteen (16) hours of interruptions per year as observed in FMEA.
- The difference in the SAIDI indices from both reliability evaluation methods is within $\pm 3\%$. These indices are also within SAIDI target of 30.89 hours in Eskom's distribution appraisal shown in Table 3.4.
- Transmission System Minutes for this feeder are 0.0094 SM. This is within the transmission target of 0.83 SM shown in Table 3.3.
- Again, there seems to be some equivalence between Eskom distribution's SAIDI and transmission's SM indices.

6.3.2.3 Observations made on the CAIDI of Umfolozi 88 kV feeder 2

- Customers on this feeder experience about three (3) hours of sustained interruptions on average in a year.
- CAIDI indices from both reliability evaluation methods are within $\pm 10\%$.

6.3.2.4 Observations made on the ASAI of Umfolozi 88 kV feeder 2

- This feeder is available to customers for approximately 99.9% of the time in a year.
- The difference in the ASAI index from both reliability evaluation methods is within $\pm 1\%$.
- The ASAI appears equivalent to the Eskom's transmission circuit availability index.

6.3.2.5 Observations made on the ASUI of Umfolozi 88 kV feeder 2

- This feeder is unavailable for about 0.1% of the time in a year.
- ASUI indices from both reliability evaluation methods are comparable.
- ASUI appears equivalent to the Eskom's transmission circuit unavailability index.

6.3.2.6 Observations made on the ENS and AENS of Umfolozi 88 kV feeder 2

- The ENS index shows high energy losses when this feeder is on outage. This has adverse consequences for Eskom utility particularly tariff price adjustment.
- Eskom's revenue losses equate to R216, 000 / year when this feeder is on outage.
- ENS indices from both reliability evaluation methods are within $\pm 1\%$.

6.3.3 Evaluation of Bloedrivier 88 kV feeder 1 reliability indices

Reliability indices for this feeder are shown in Table B.3 and these results are compared.

6.3.3.1 Observations made on the SAIFI of Bloedrivier 88 kV feeder 1

- This feeder experiences about five (5) hours of supply interruptions per year as observed from the FMEA results.
- SAIFI indices from both reliability evaluation methods are within $\pm 10\%$.
- These indices are within the Eskom's distribution SAIFI target of 20.22 minutes in Table 3.4
- Similarly, there are similarities between this index and Eskom transmission's NOI.

6.3.3.2 Observations made on the SAIDI of Bloedrivier 88 kV feeder 1

- This feeder experiences about twenty-seven (27) hours of supply interruption per year as observed from the FMEA results.
- SAIDI indices from both reliability evaluation methods are within $\pm 1\%$.
- The SAIDI of this feeder is within Eskom's distribution SAIDI target value of 30.89 hours in Table 3.4.
- Transmission Systems Minutes of this feeder is 0.0595 SM. This is within the 0.83 SM target shown in Table 3.3.
- Again, there seems to be some equivalence between Eskom's distribution SAIDI and Eskom's transmissions SM index.

6.3.3.3 Observations made on the CAIDI of Bloedrivier 88 kV feeder 1

- Customers on this feeder experience about twelve (12) minutes of sustained interruptions on average in a year.
- CAIDI indices from both reliability evaluation methods are within $\pm 3\%$.

6.3.3.4 Observations made on the ASAI of Bloedrivier 88 kV feeder 1

- This feeder is available for customers approximately 99.8% of the time in a year.
- ASAI indices from both reliability evaluation methods are within $\pm 1\%$.
- Again, ASAI appears equivalent to the circuit availability index in Table 3.3.

6.3.3.5 Observations made on the ASUI of Bloedrivier 88 kV feeder 1

- This feeder is unavailable for about 0.2% of the time in a year.
- ASUI indices from both reliability evaluation methods are comparable.
- The ASUI also appears to be equivalent to the Eskom's transmission circuit unavailability index in Table 3.3.

6.3.3.6 Observations made on the ENS and AENS of Bloedrivier 88 kV feeder 1

- ENS index shows high energy losses.
- This ENS has adverse consequences on Eskom's tariff price adjustments especially since these customers (Transnet) are large power users.
- This equates to about R273,000 revenue loss/year to Eskom when this feeder is on outage.
- Transnet also losses a lot of money when trains are stuck on the rails. This adversely impacts the economy of the Country. NERSA may also impose penalties and withhold incentives.
- ENS indices from both reliability evaluation methods are within $\pm 1\%$.

6.4 Modelling and simulation of the EGTN in PSB, PSAT and ATP tools

Modelling methodologies of the EGTN in PSB, PSAT and ATP simulation tools are discussed in this section. Simulation results of the EGTN under different contingencies from these tools are also presented and discussed. The assessment of each simulation tool is also given. Each simulation package requires that a power network be modelled and represented in the format that allows the convergence of the power flow. The capability, accuracy and robustness of a simulation tool are assessed on how a network can be logically constructed and simulated in that specific simulation tool [7]. This allows uniformity in the computation of desired parameters and comparison of simulation tools. In this section, different models for each simulation tool are proposed for the performance evaluation of surge arresters in the EGTN. The surge arresters at Umfolozi, Bloedrivier, Normandie and Empangeni i.e., bus #1, 3, 5 and 7 are evaluated under each tool.

6.5 Proposed model of the traction network in PSB tool

In the PSB tool, the grid and traction network for surge arrester performance evaluation are modelled as a voltage source, line breaker (BKR), line and the traction load as shown in Figure 6.3.

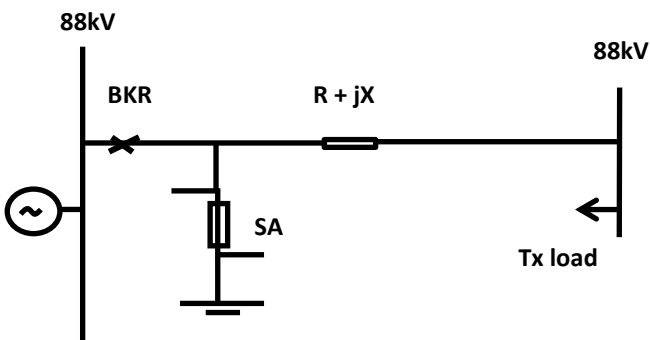


Figure 6.3: The proposed model for surge arrester studies in PSB tool

6.5.1 Application of the proposed PSB model in EGTN

The proposed model in Figure 6.3 is expanded to model the EGTN as a 7-bus system in the PSB tool. Umfolozi, Bloedrivier, Normandie and Empangeni substations are modelled as busbars that are numbered 1, 3, 5 and 7 respectively, as shown in Figure 6.4.

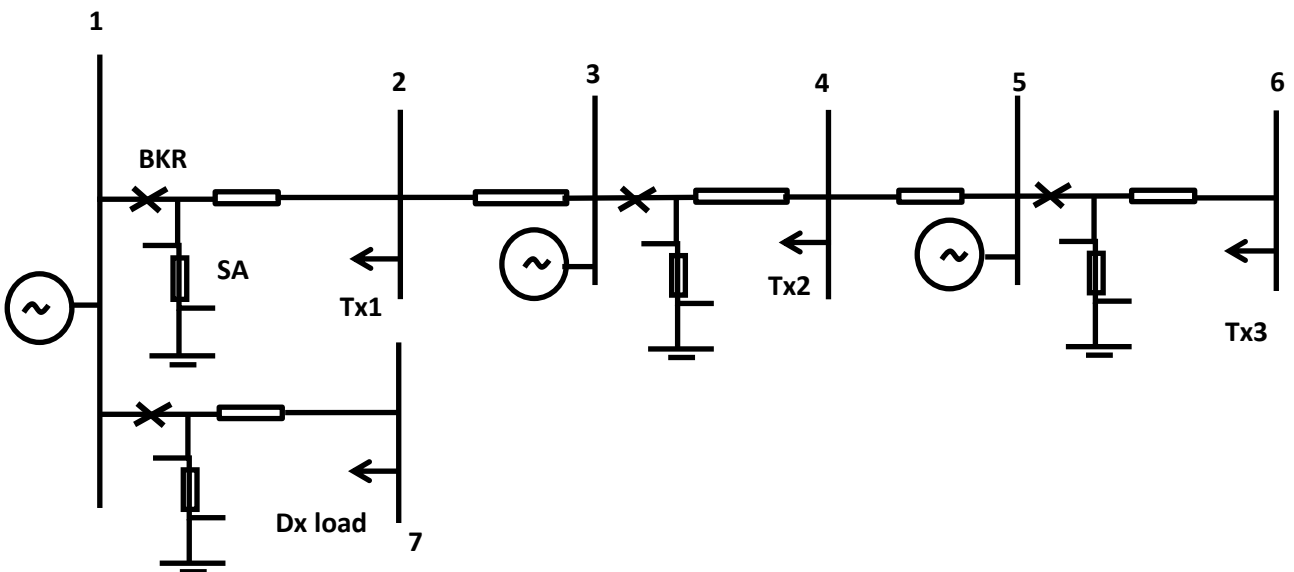


Figure 6.4: The application of the proposed model in the EGTN for PSB simulations

6.5.2 Description of the EGTN model parameters and simulation method in PSB

Umfolozi, Bloedrivier and Normandie substations are modelled as sinusoidal voltages with RMS voltages of 88 kV. Transmission lines are modelled as π sections with 76.8 km line lengths strung in Wolf conductor. R, L and C parameters of a Wolf conductor are specified in [77] as $0.1932 \Omega/\text{km}$, $614.9 \times 10^{-6} \text{ H/km}$ and $13.419 \times 10^{-9} \text{ F/km}$, respectively as shown in Table A.4. In the EGTN model in Figure 6.4, surge arresters are modelled by connecting surge arrester blocks at buses 1, 3, 5 and 7. Traction loads are modelled as power factor varying PQ loads namely Tx1, Tx2, Tx3 at buses 2, 4 and 6. The distribution load is modelled as a variable load, Dx at bus 7.

Faults are modelled and initiated by controlling signal generators that change the amplitude between logic 1 and 0. Breakers are modelled as switches buses 1, 3, 5 and 7 that change positions depending on the amplitude of the signal generator. These signals control breaker statuses such that logic 1 indicates a breaker in a closed position. Logic 0 indicates the breaker in an open position, thus breaker contacts are closed for no fault conditions and opened under fault conditions. Fault blocks are configured with breaker changing states such that at 1 second the fault is initiated i.e., signal generator changes amplitude from 1 to 0 (breaker is opened). The fault clearance is configured such that at 1.04 seconds, the fault is cleared i.e., the signal generator changes amplitude from 0 to 1 (breaker is closed) as illustrated in Figure 6.5. This configuration and speed of protection is chosen because faults in Eskom transmission's 88 kV networks are cleared within 40 ms (2 cycles). The EGTN model data for PSB simulations is shown in Table A.4.

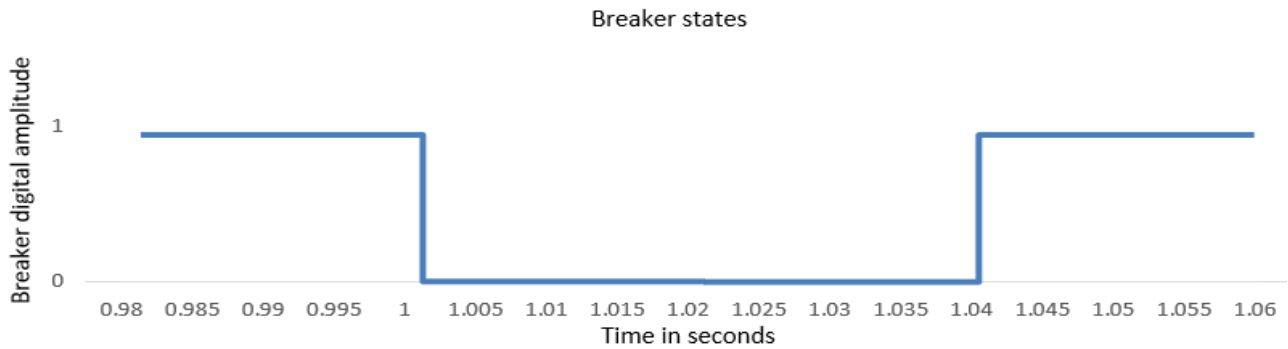


Figure 6.5: The timing diagram illustrating fault clearing times and breaker states

Breaker states are created by assigning variables in the workspace that can be recalled by their specific names as vectors in the MATLAB command window. Current and voltage meters are also used for plotting. Steady state voltages are conditions when there are no faults in the network. Steady state busbar voltages result for each network loading condition namely 1, 0.85 and 0.7 power factors are logged.

Faults are then sequentially initiated at buses 1, 3, 5 and 7 and busbar voltage and surge arrester currents are plotted for each transient condition. The energy stored in the surge arrester under a fault condition is then evaluated over the fault period shown in Figure 6.5. Busbar 1, 3, 5 and 7 surge arrester parameters i.e., continuous operating voltages (U_c), rated voltages (U_r), discharge currents (I_d) and energy absorption capabilities (EACs) are then evaluated. These parameters are compared against parameters specified by ABB, Siemens and Areva original equipment manufacturers (OEMs) and parameters specified by Eskom in [74].

6.6 EGTN modelling and simulation in PSAT

EGTN in this tool is modelled as a 3 machine, 10 bus system with synchronous generators equipped with automatic voltage regulators (AVRs). These generators are connected at buses 1 (Umfolozi), 3 (Bloedrivier) and 5 (Normandie) as shown in Figure 6.6.

6.6.1 Description of the EGTN model parameters and simulation method in PSAT

Power infeeds into Umfolozi, Bloedrivier and Normandie substations are modelled as synchronous generators connected to PV buses as shown in Figure 6.6. In order to regulate voltages at Umfolozi, Bloedrivier and

Normandie substations, automatic voltage regulators are connected on the HV busbars. Umfolozi, Bloedrivier and Normandie generator parameters are shown in Table A.5. Umfolozi substation is modelled as a 400/88 kV two winding transformer. Bloedrivier and Normandie substations are modelled as two winding 275/88 kV transformers with parameters as shown in Table A.6.

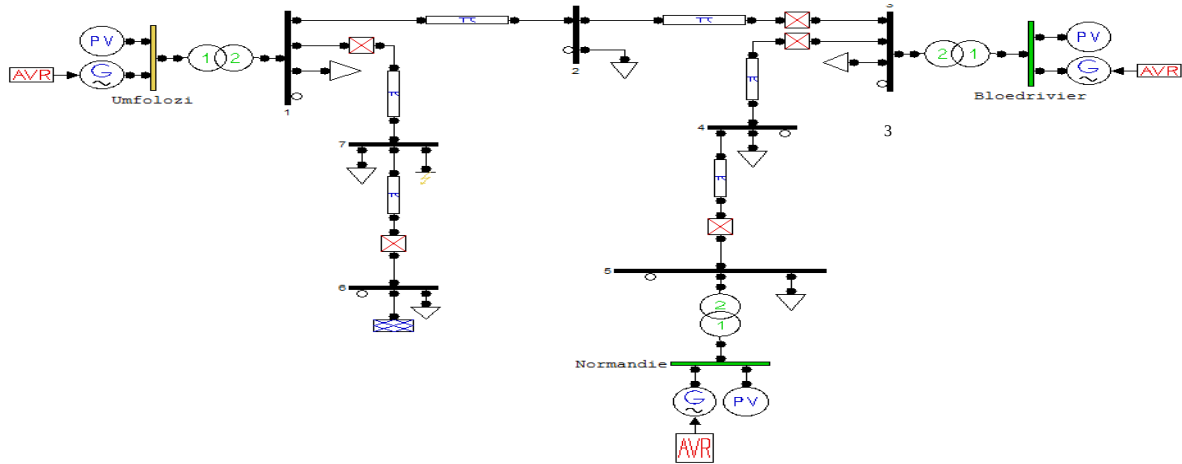


Figure 6:6: The EGTN model in PSAT

The distribution load is modelled as a resistive load connected to an infinite bus at bus 6. In PSAT, power flow is run before the transient simulation, therefore the power to other parts of the networks needs to be considered. This power is modelled as real loads at buses 1, 3, 5 and 7 to prevent non-convergence errors in the power flow simulations. Traction loads vary between 0.7, 0.85 and unity power factors and are shown in Table A.6.

Transmission lines are modelled as π sections with 76.8 km line lengths strung in Wolf conductor as shown in Table A.4. Traction loads (Tx1, Tx2 and Tx3) are modelled as PQ loads at buses 2, 4 and 7 respectively, under different power factors. EGTN's model line and load data for PSAT simulations are shown in Tables A.5 and A.6.

A fault is modelled with fault block in PSAT library with the fault starting at 1.0 second and clearing at 1.04 seconds with fault parameters as shown in Table A.7. Steady state busbar voltages and steady state load results for each network loading condition are logged for 1, 0.85 and 0.7 power factors.

Faults are then sequentially initiated at buses 1, 3, 5 and 7, busbar voltage and surge arrester currents are plotted for each transient condition. Continuous operating voltages (U_c) and rated voltages (U_r) parameters are computed for surge arresters at these buses. These parameters are then compared against 88 kV surge arrester parameters from ABB, Siemens and Areva datasheets and the Eskom 88 kV surge arrester specification.

6.7 EGTN modelling and simulation in ATP tool

The EGTN is modelled in ATP as a 7-bus system with 88 kV sinusoidal voltages at buses 1, 3 and 5 as shown in Figure 6.7. The numbering of buses in this tool is the same as that in the PSB tool. EGTN's AC voltage source input parameters are shown in Table A.8.

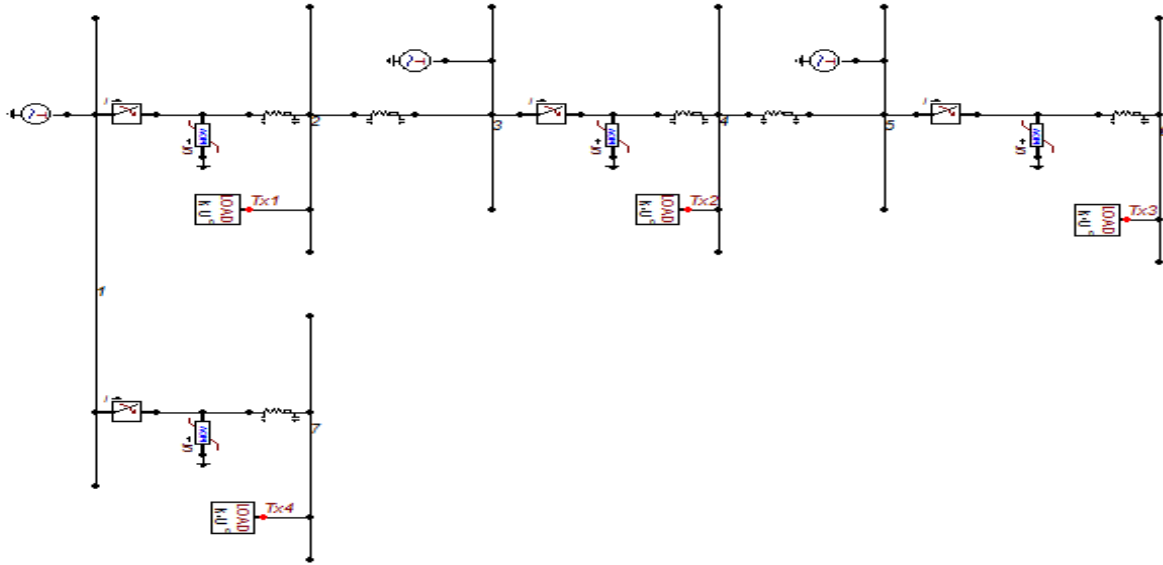


Figure 6.7: The EGTN model in ATP

6.7.1 Description of the EGTN model parameters and simulation method in ATP tool

The model of the EGTN in ATP tool has a similar structure as that for PSB tool i.e., transmission lines are modelled as π sections with 76.8 km line lengths strung in Wolf conductor. The same line and load data used in PSB tool (Table A.3) is used in the ATP tool. Breakers in this tool are modelled as switch blocks which change states a number of times between open and close states very fast i.e., open for 0.01 seconds and closed for 1 second. This is because ATP is an electromagnetic transient tool (EMT) and does not require a manual creation of faults at specific busbars as it is the case with the PSB tool. Instead, the transient fault is modelled by fast switching of breaker states thus generating switching voltage impulses at buses 1, 3, 5 and 7.

Surge arresters are modelled by connecting MOV blocks at buses 1, 3, 5 and 7 as shown in Figure 6.7. Traction and the distribution loads are modelled as PQ loads at buses 2, 4, 6 and 7 for different loading conditions. Steady state busbar voltages under no fault conditions in the network are computed for network conditions at 1, 0.85 and 0.7 power factors. Busbar voltages and surge arrester currents are plotted for each transient condition. The energy stored in the surge arrester under a fault condition is then evaluated over the fault duration i.e., 0.04 second. Continuous operating voltages (U_c), rated voltages and energy absorption capabilities (EACs) parameters are computed for surge arresters at buses 1, 3, 5 and 7. These parameters are then compared against 88 kV surge arrester parameters from ABB, Siemens and Areva datasheets and Eskom specifications.

Chapter 7.

7.1 Presentation and discussion of PSB, PSAT and ATP simulation results

In this chapter simulation results of the EGTN are presented and discussed. Comparisons of surge arresters parameters computed from these tools are also made.

7.2 Steady state simulation results of the EGTN in PSB tool

The results presented in this section give an overview of the steady state voltages in the network and how these buses may be impacted when transient faults are initiated in the network. These simulations are run for each loading condition and when breakers at buses, 1, 3, 5 and 7 are closed. EGTN breaker states in steady state condition for all load conditions namely 0.7, 0.85 and unity power factors are shown in Figure 7.1.

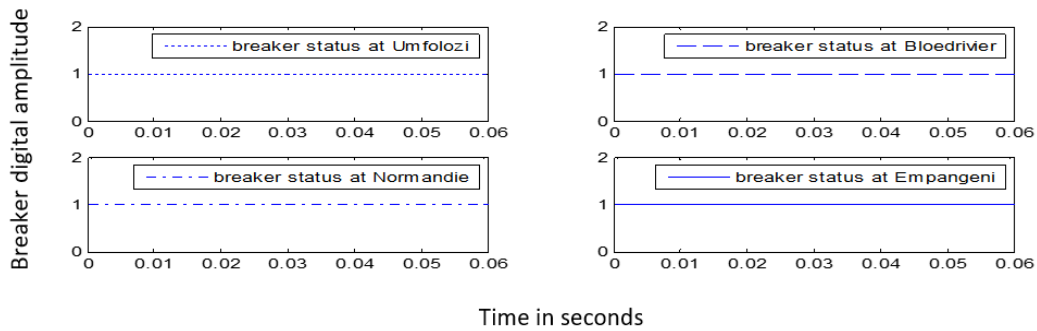


Figure 7.1: Breaker states in PSB steady state simulations for all EGTN loading conditions

Umfolozi, Bloedrivier, Normandie and Empangeni breakers are closed as expected during steady state conditions as there are no faults in the EGTN.

7.2.1 EGTN 88 kV steady state busbar and surge arrester voltages at full load conditions

The voltages of interest under this network are at buses 1, 3, 5 and 7. It can be noted that under steady state conditions the peak voltage at bus 6 is higher than any other voltages in the EGTN as shown in Figure 7.2. It is evident in this figure that voltages at buses 1, 3, 4 and 5 are overlaid and not visible. In order to address this these voltages are called from the MATLAB command window and exported to Microsoft Excel for clearer graphical representation.

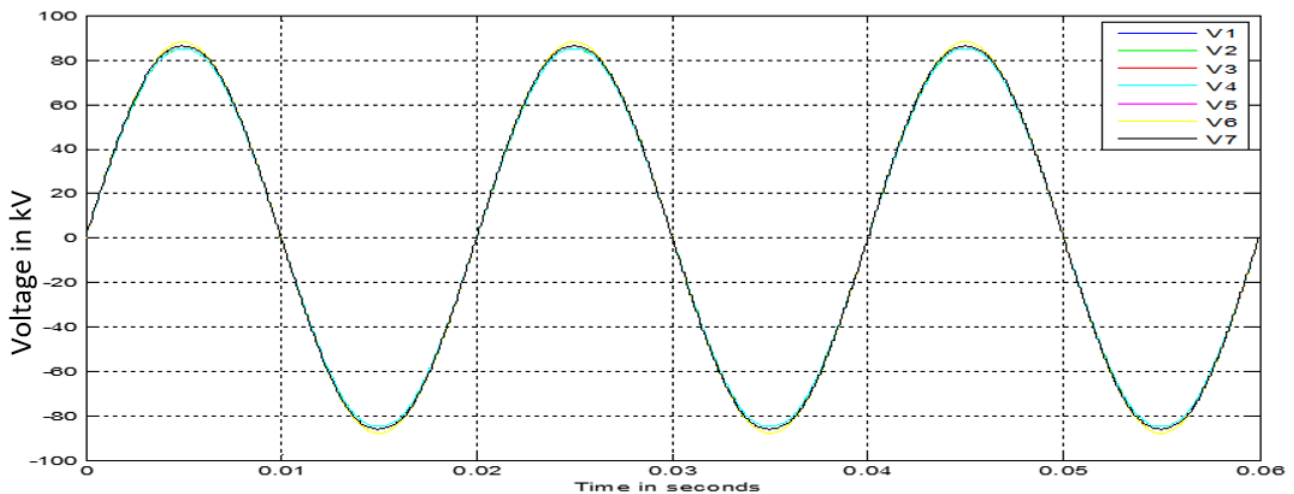


Figure 7.2: EGTN steady state peak voltages generated from PSB at full load at different buses.

Voltages at buses 1 – 7 are then plotted as shown in Figure 7.3 where surge arresters at buses 1, 3, 5 and 7 are of interest.

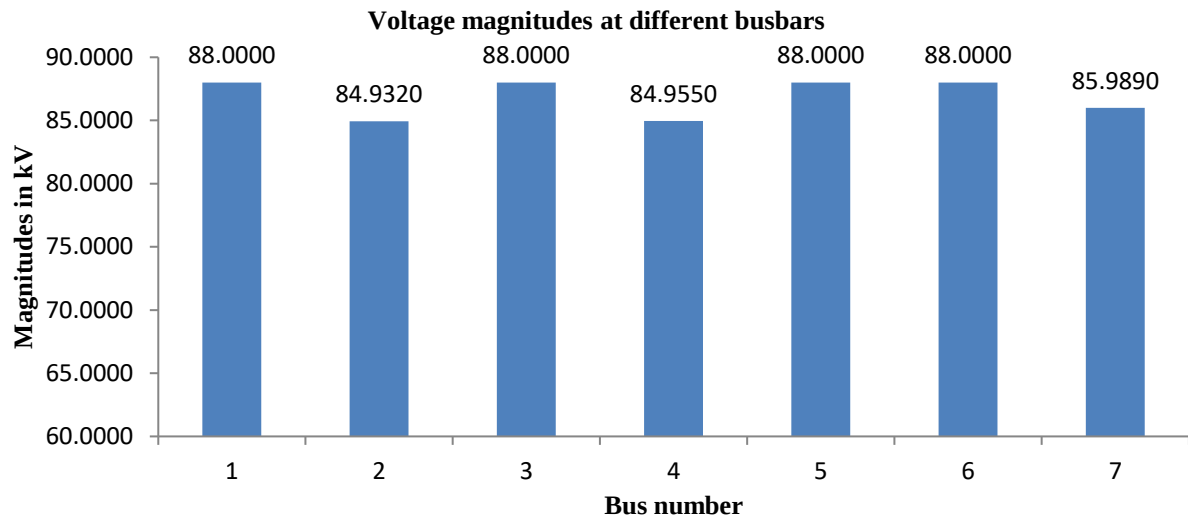


Figure 7.3: Steady state peak voltage magnitudes in all EGTN buses at full loading

In the simulations that follow voltages at buses 1, 3, 5 and 7 are examined to evaluate if surge arresters at these buses conduct under each transient fault condition in the network.

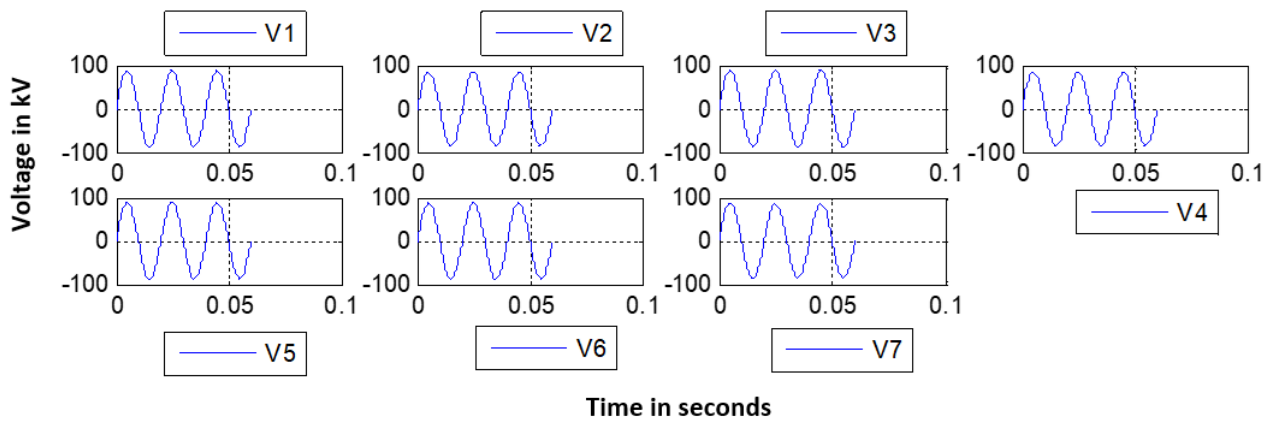


Figure 7.4: Individual busbar steady state voltages at full loading

Surge arrester voltages in the EGTN are all perfectly sinusoidal as there are not faults in this network under steady state conditions as observed in Figures 7.4 and 7.5.

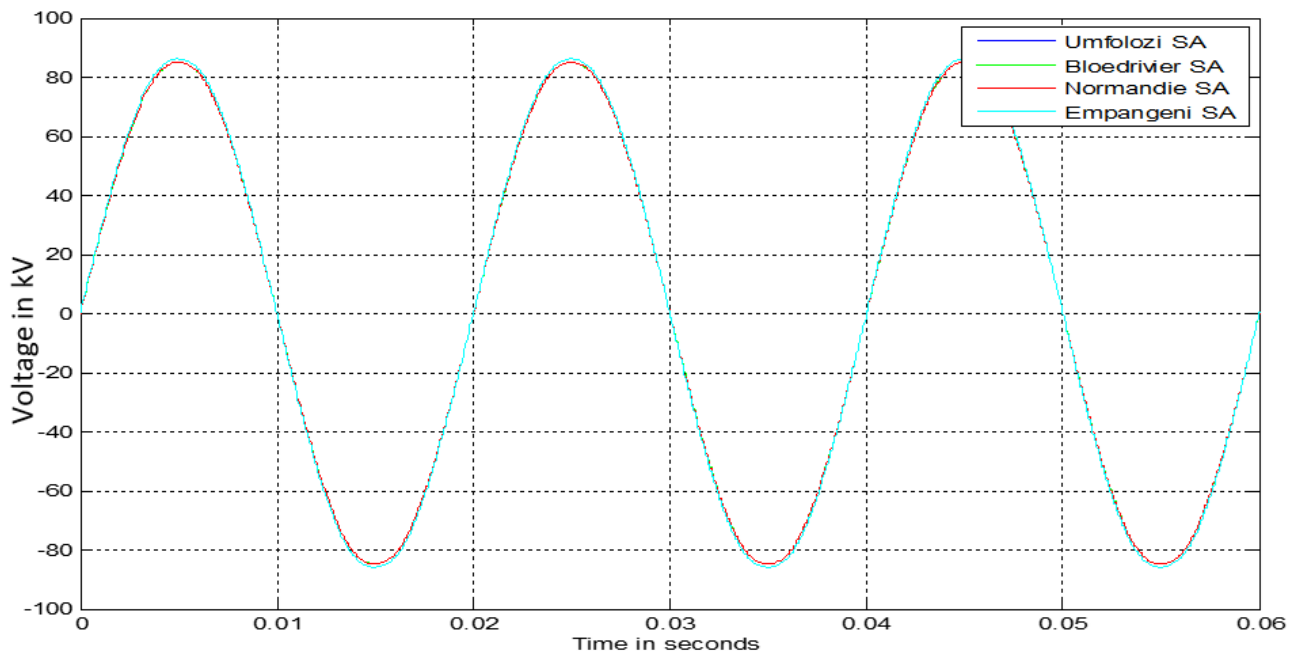


Figure 7:5: Steady state surge arrester peak voltages at traction stations in the EGTN

Surge arrester voltages under steady state conditions are shown in Figure 7.6.

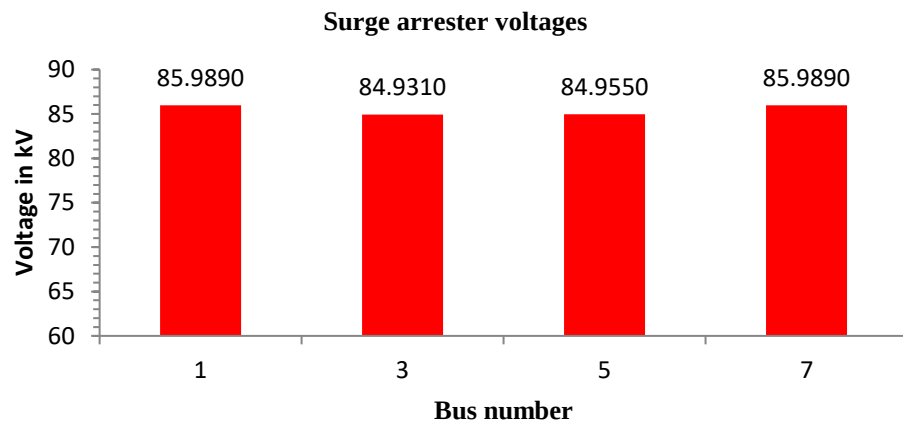


Figure 7:6: Surge arrester steady state voltage magnitudes

7.2.2 EGTN 88 kV steady state busbar and surge arrester voltages at 0.85pf

Busbar voltages under this contingency are shown in Figure 7.7 and 7.8.

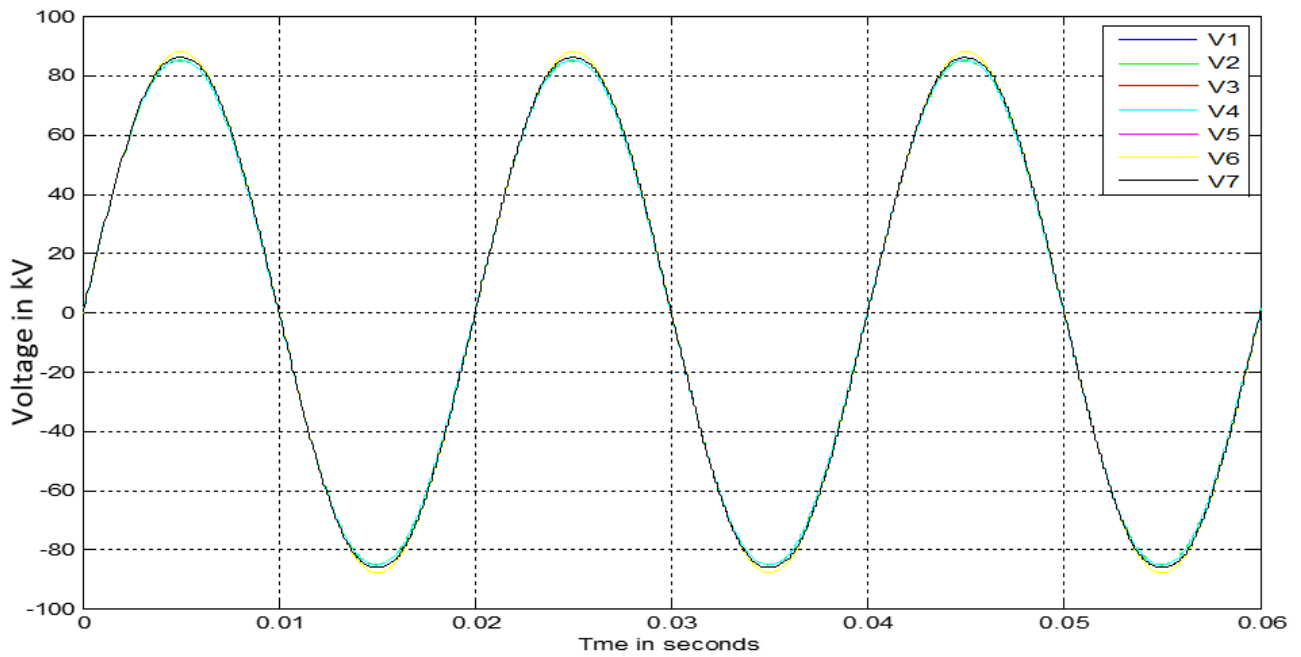


Figure 7:7: EGTN steady state voltage profiles generated from PSB at full loading.

Voltages at buses 1, 3, 5, 6 and 7 are dominant under steady state conditions as observed in Figure 7.8.

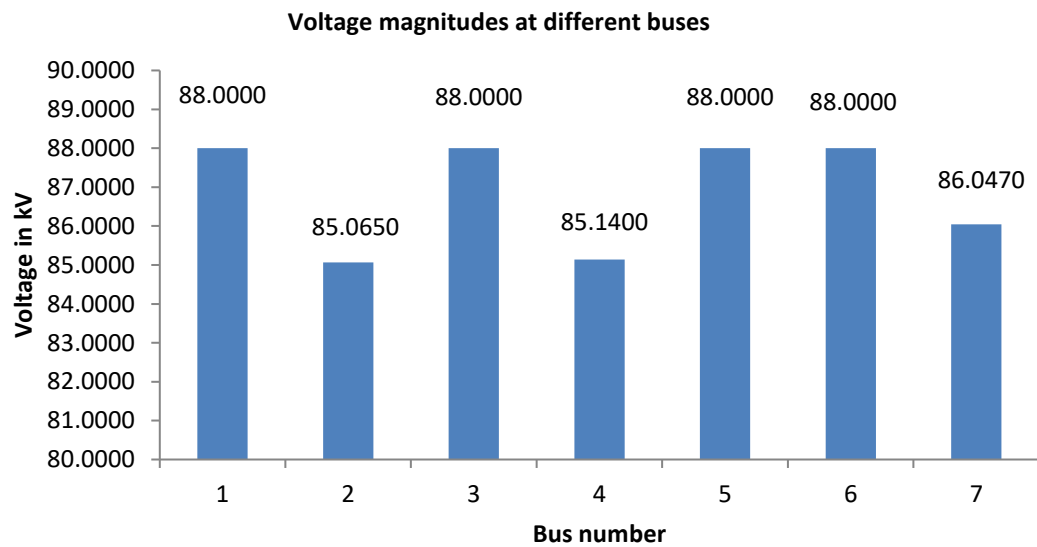


Figure 7:8: Steady state voltage magnitudes in all EGTN buses

Surge arrester voltages under this contingency are shown in Figure 7.9.

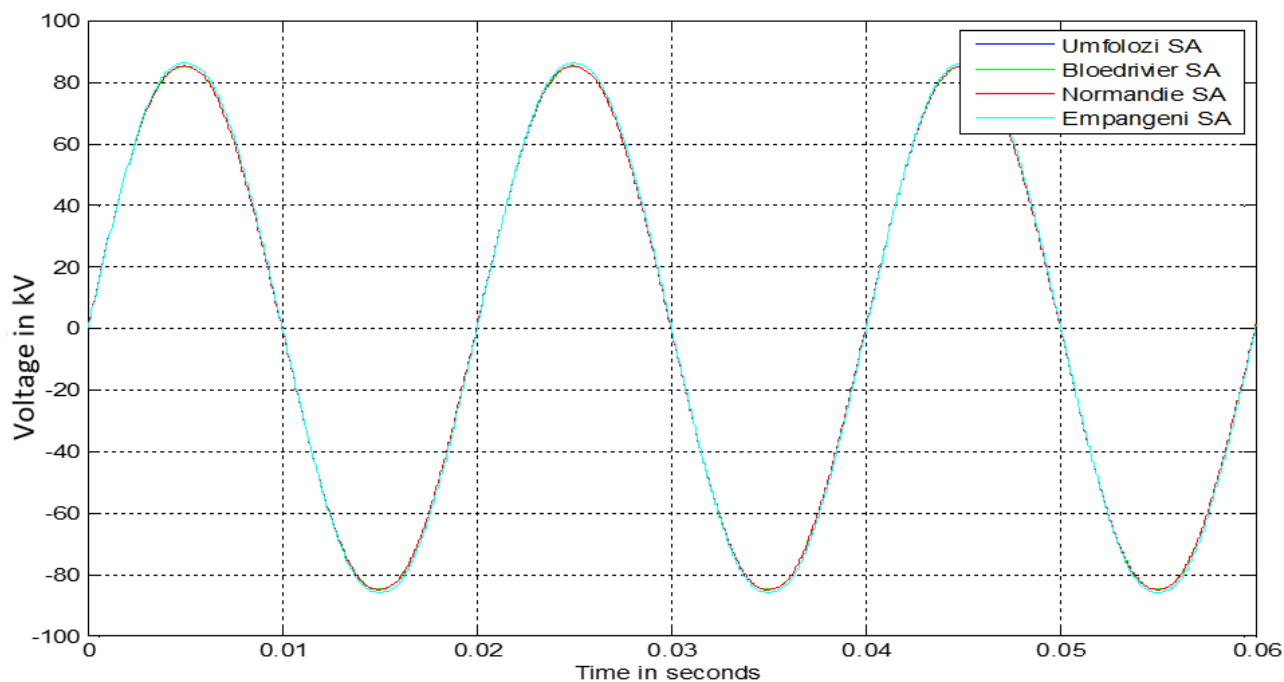


Figure 7:9: Steady state surge arrester voltages at traction stations in the EGTN

The Empangeni surge arrester is dominant as shown in Figure 7.9. Figures 7.10 and 7.11 indicate that as the power factor worsens from unity to 0.85 busbar and surge arrester voltages increases.

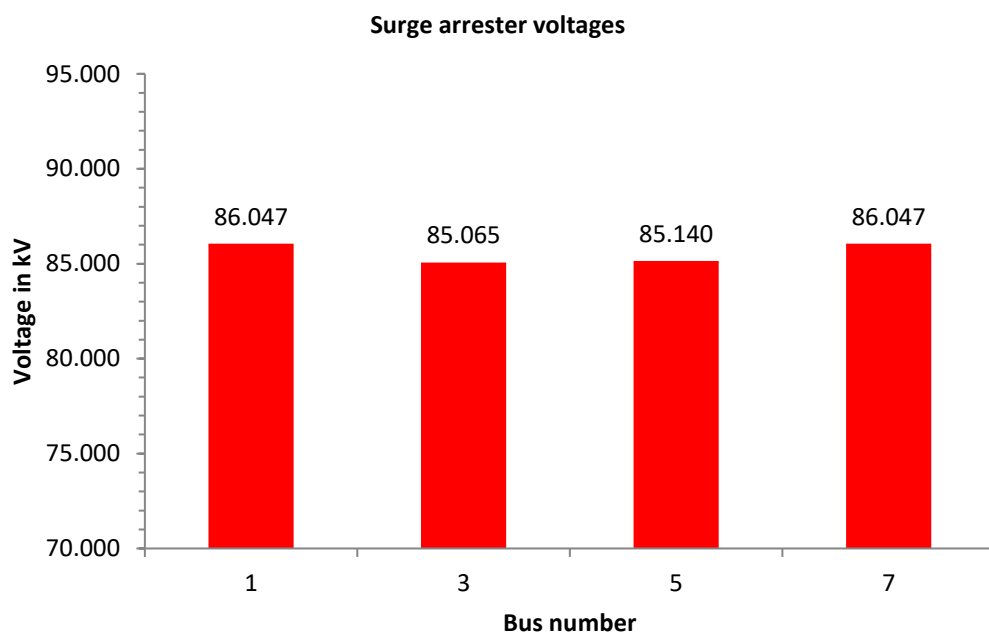


Figure 7:10: Surge arrester steady state peak voltages

7.2.3 EGTN 88kV steady state busbar and surge arrester voltages at 0.7pf

The voltage at bus 6 is higher than other voltages in Figure 7.11.

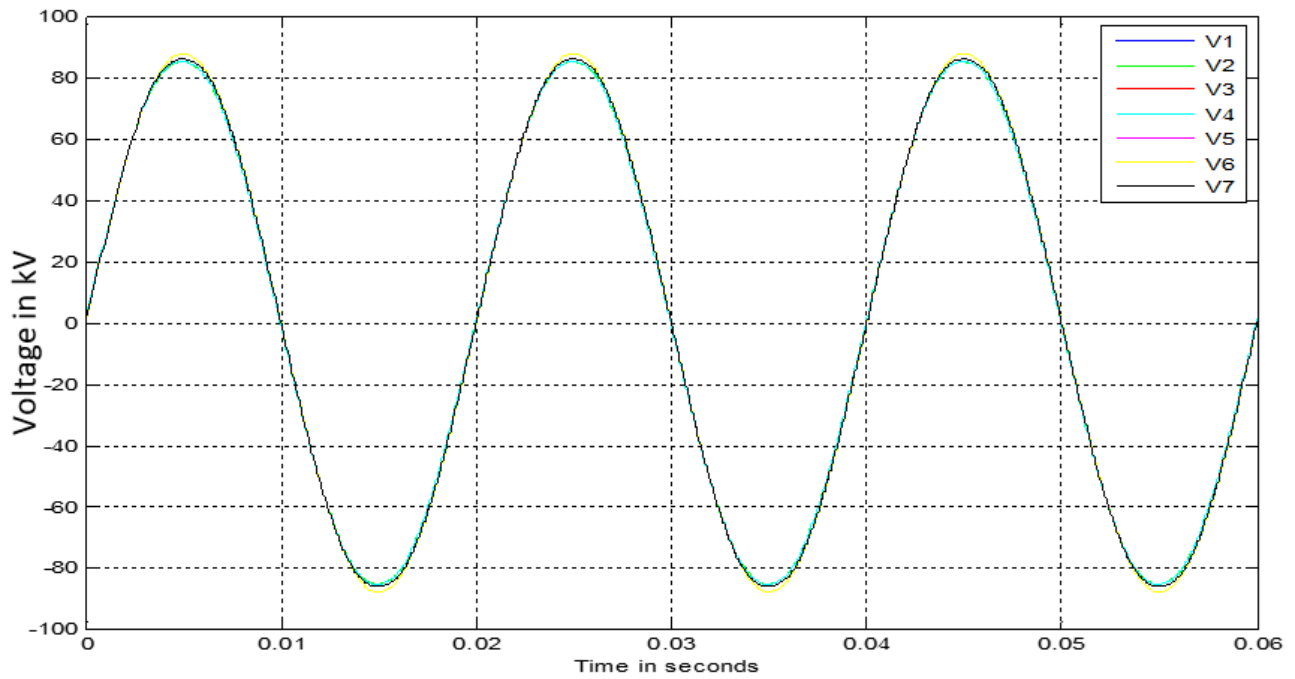


Figure 7:11: EGTN steady state voltage profiles generated from PSB at 0.7 pf loading

Busbar voltages under steady state conditions are shown in Figure 7.12.

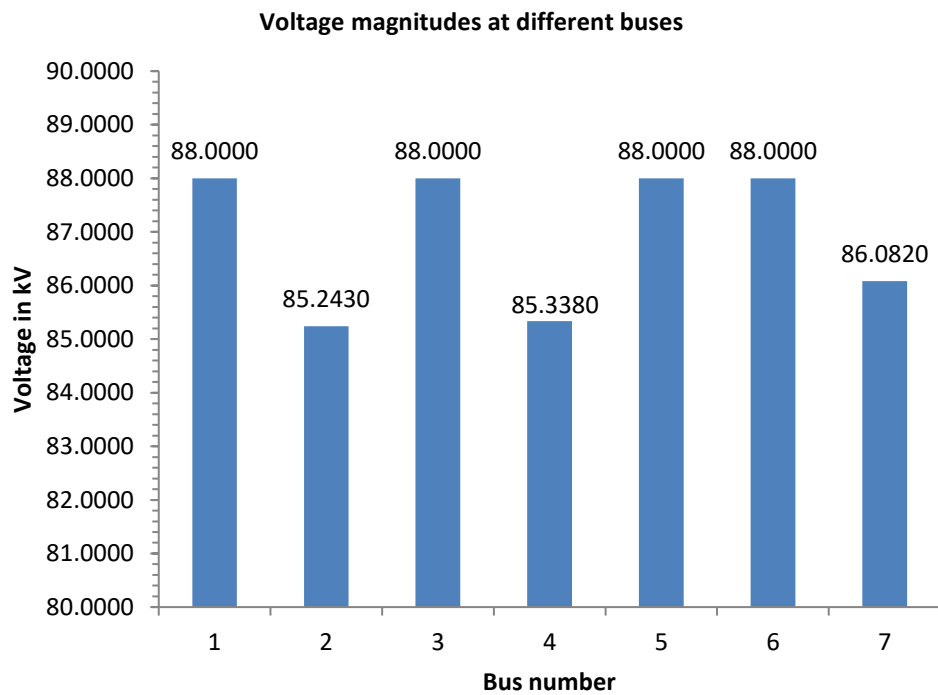


Figure 7:12: Steady state peak voltages in all EGTN buses

It can be observed in Figure 7.13 that the Empangeni surge arrester voltage is higher as it was the case at unity and 0.85 pf loading conditions above.

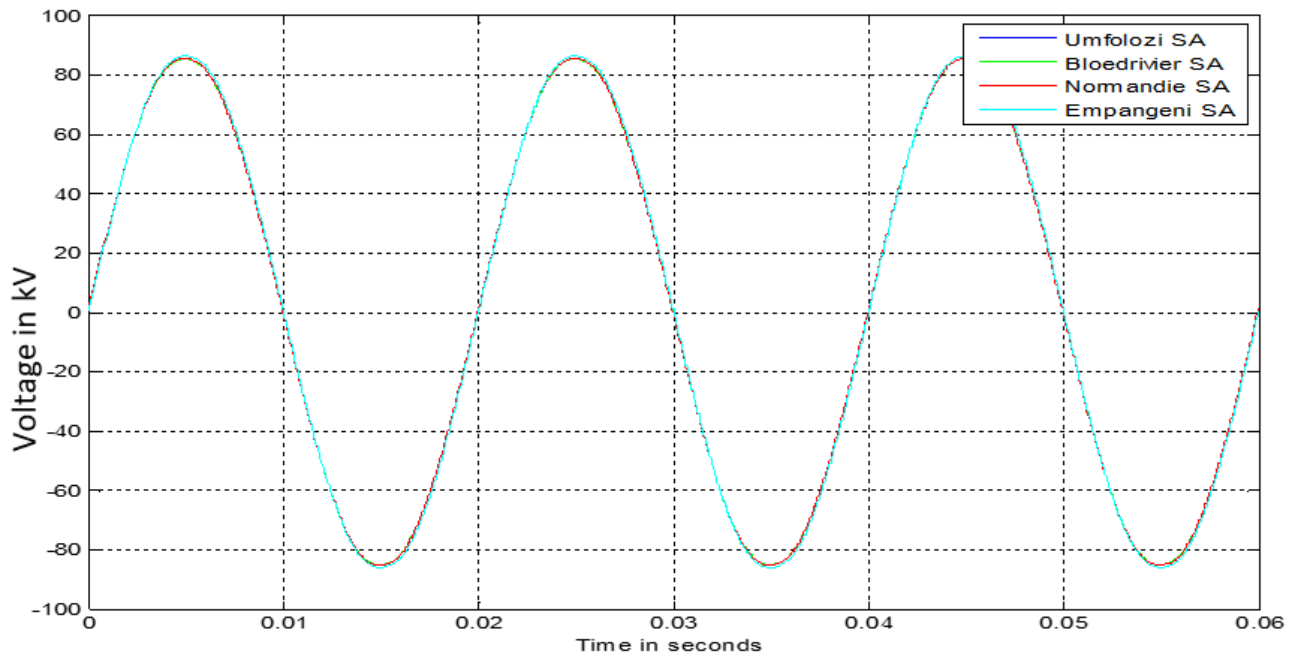


Figure 7.13: Steady state surge arrester peak voltages at traction stations in the EGTN

The surge arrester voltages in the EGTN under steady state conditions at $0.7pf$ are shown in Figure 7.14.

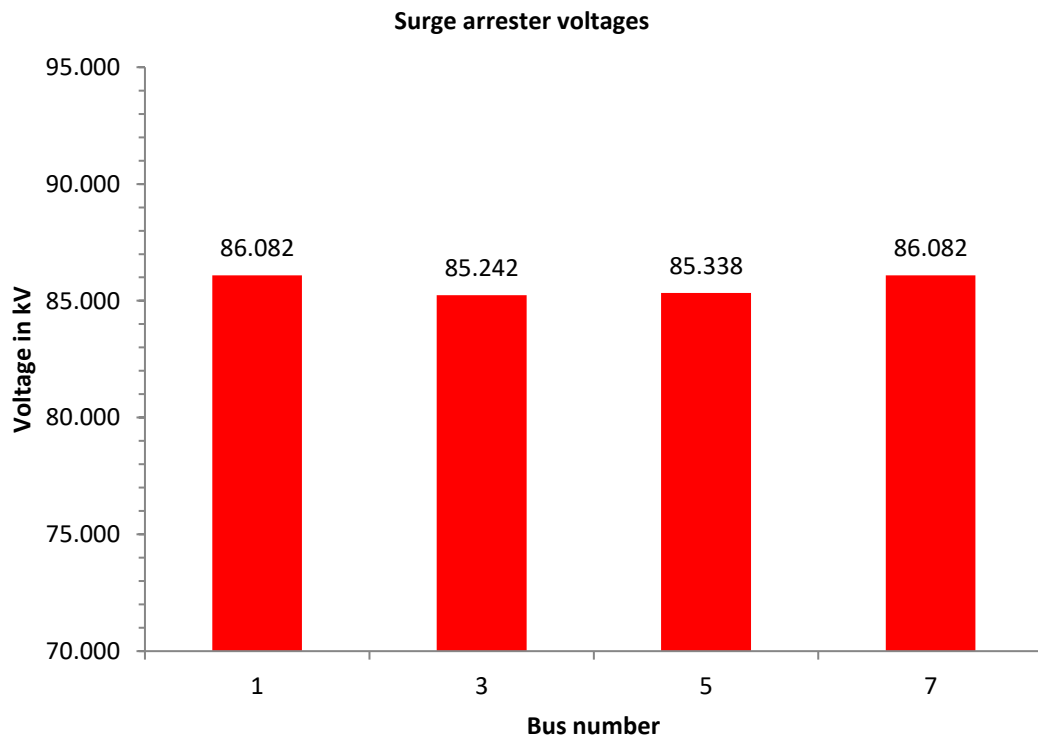


Figure 7.14: Surge arrester steady state peak voltages

The above simulations show that the voltage magnitudes at buses 2, 4 and 7 increases as the power factor deteriorates from $1pf$ to $0.7pf$ as shown in Figure 7.15. This is expected due to the inverse relationship between

the voltage and power factor. However, busbar voltages closer to generators such as buses 1, 3, 5 and 6 as shown in Figure 6.6 remain unchanged.

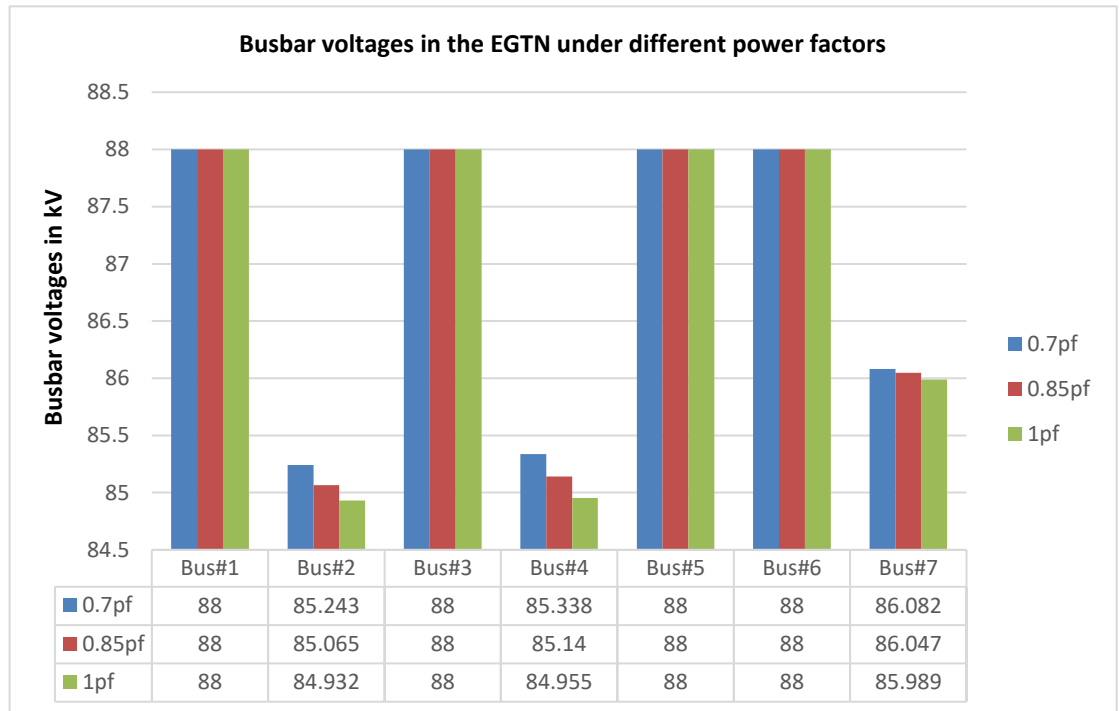


Figure 7:15: Busbar voltages in the EGTN under different loading conditions

7.3 Transient state simulation results of the EGTN model in PSB tool

The transient state voltages in the EGTN shown below as busbar voltage profiles and surge arrester voltages assists in evaluating surge arrester parameters on surge arresters that were impacted by transient faults. These fault conditions arise due to sequential faults occurring at buses 1, 3, 5 and 7 in the EGTN. U_c , U_r , I_d and EAC parameters of each surge arrester under loading conditions and specific transient states are evaluated.

7.3.1 Breaker states for a fault at Umfolozi at full loading, 1pf

Umfolozi breaker opens and closes as expected under this contingency as shown in Figure 7.16.

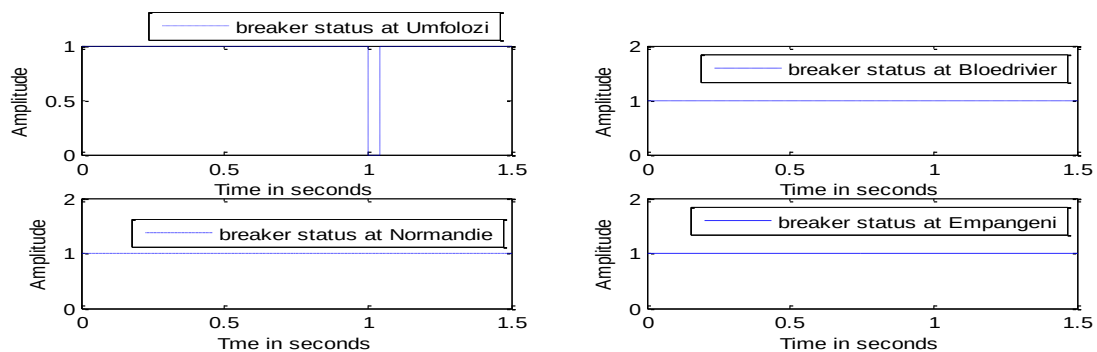


Figure 7:16: Breaker states for a fault at Umfolozi

7.3.2 Surge arrester voltage and current waveforms for a fault at Umfolozi at full loading

The surge arrester at bus 1 clamps the voltage under this contingency as expected (Figure 7.17). Surge arrester voltages at buses 1 and 7 are equal (85.989 kV) whilst the voltage magnitudes at buses 3 and 5 are 84.933kV and 84.956kV, respectively (Figure 7.18).

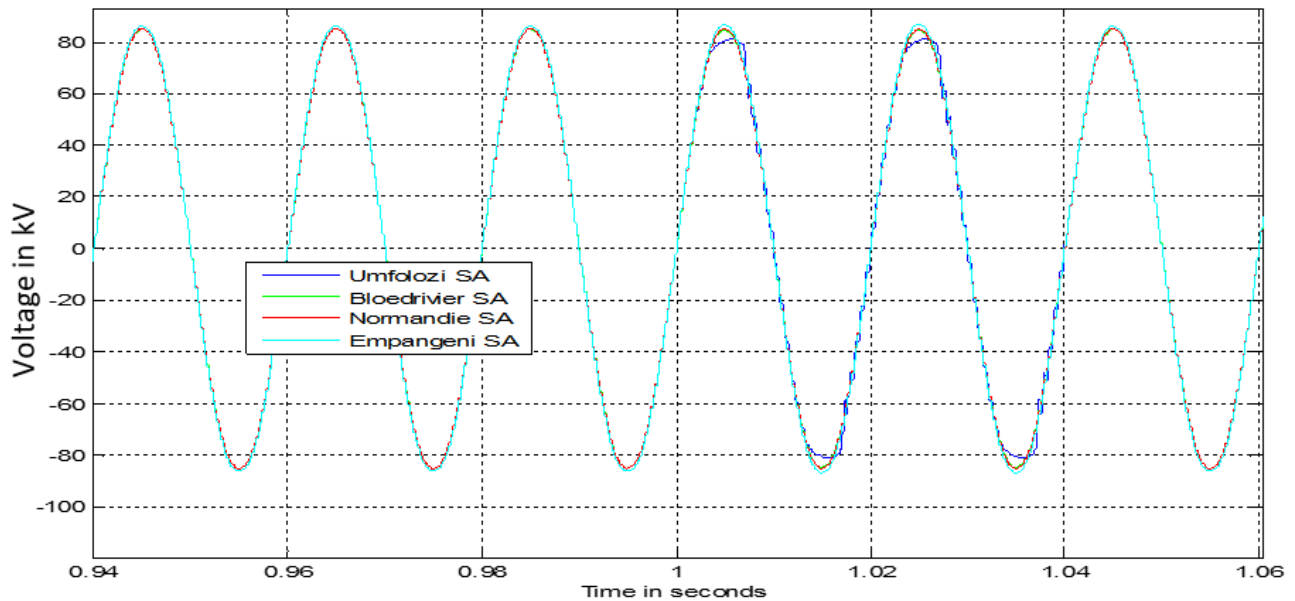


Figure 7.17: Surge arrester voltages during a transient fault at Umfolozi

The current through the Umfolozi surge arrester as it conducts under this contingency is about 0.8667A; the remaining surge arresters in the EGTN do not conduct as observed in Figure 7.19.

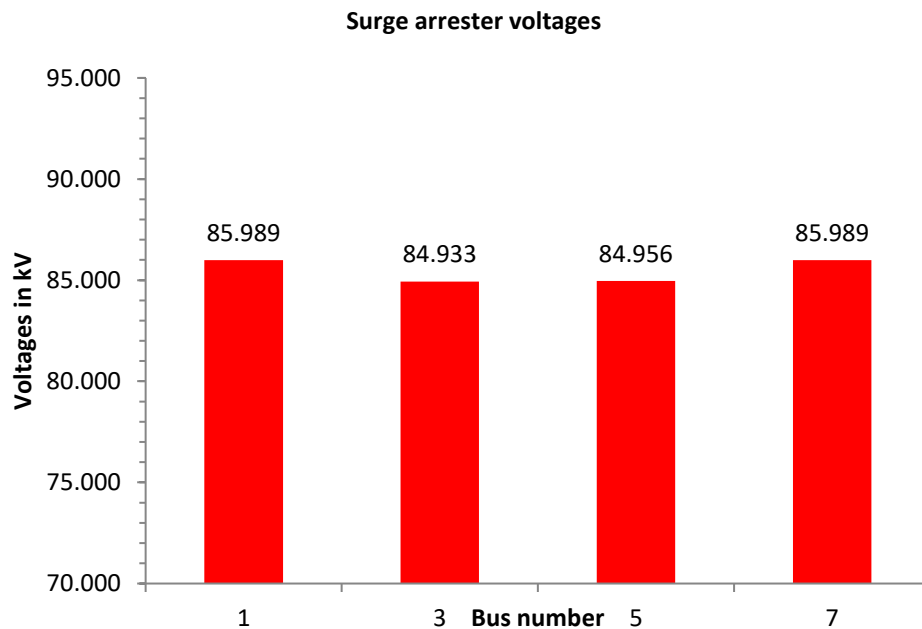


Figure 7.18: Transient voltage magnitudes in the EGTN during a fault at Umfolozi

It should be noted that currents in Figures 7.19, 7.23, 7.28 and 7.32 surge arrester current magnitudes are actually very small but seem high because they are plotted on the same scale as line currents. Line currents in pre- and post-fault conditions at buses 1, 3 and 7 are approximately 600 A whilst the line current at bus 5 is approximately 1000 A.

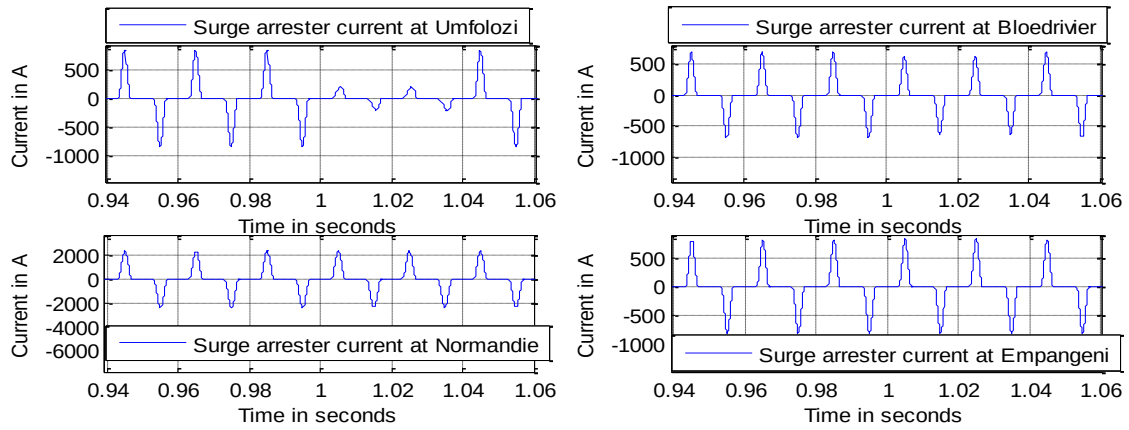


Figure 7:19: Surge arrester current waveforms in the EGTN during a transient fault at Umfolozi

7.3.3 Breaker states for a fault at Bloedrivier at full loading

Bloedrivier breaker opens and closes as expected under this contingency (Figure 7.20).

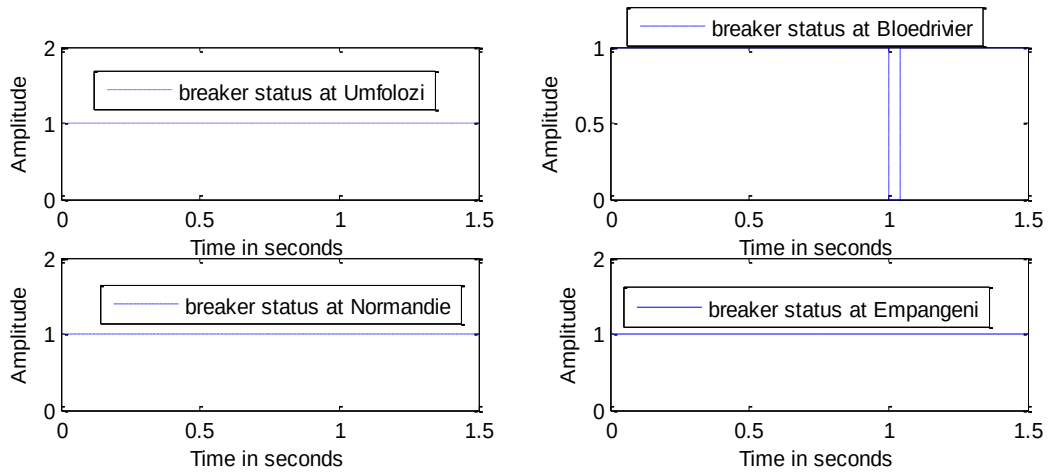


Figure 7:20: Breaker states in the EGTN under a transient fault at Bloedrivier

7.3.3.1 Surge arrester voltage and current waveforms for a fault at Bloedrivier at full loading

Bloedrivier surge arrester clamps the voltage under this contingency as expected (Figure 7.21).

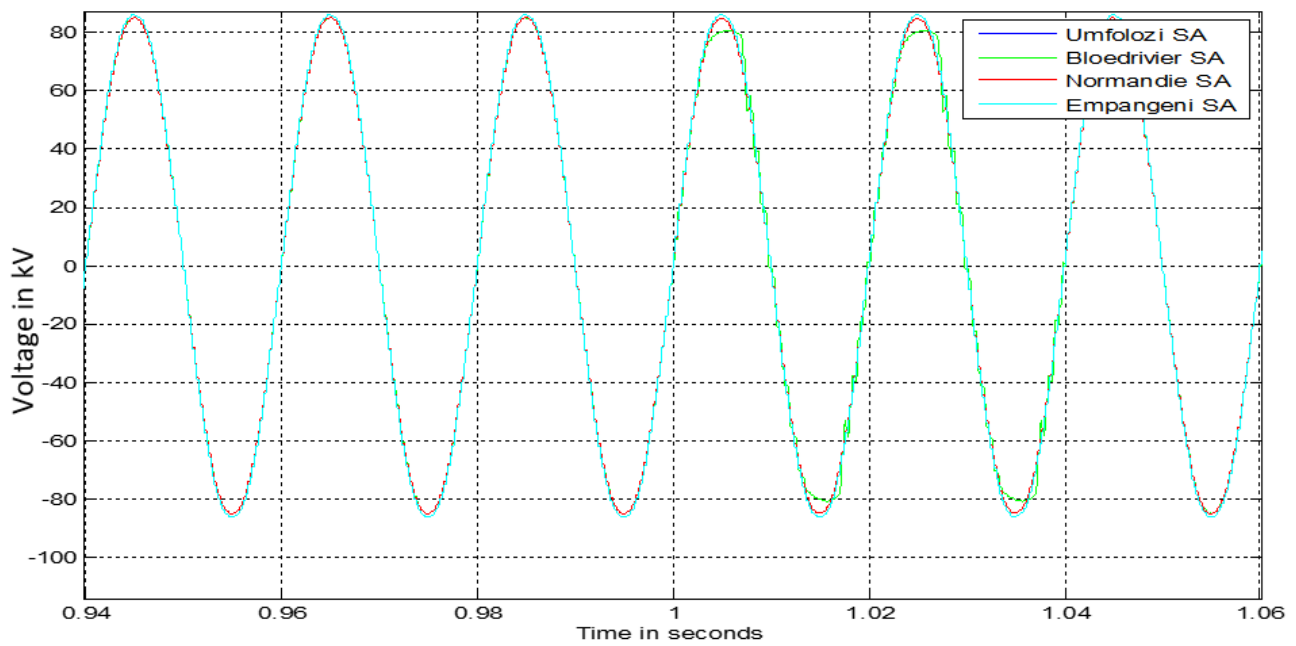


Figure 7:21: Voltage magnitudes in the EGTN for a fault at Bloedrivier

Surge arrester voltage at bus 5 under this voltage is dominant as observed in Figure 7.22.

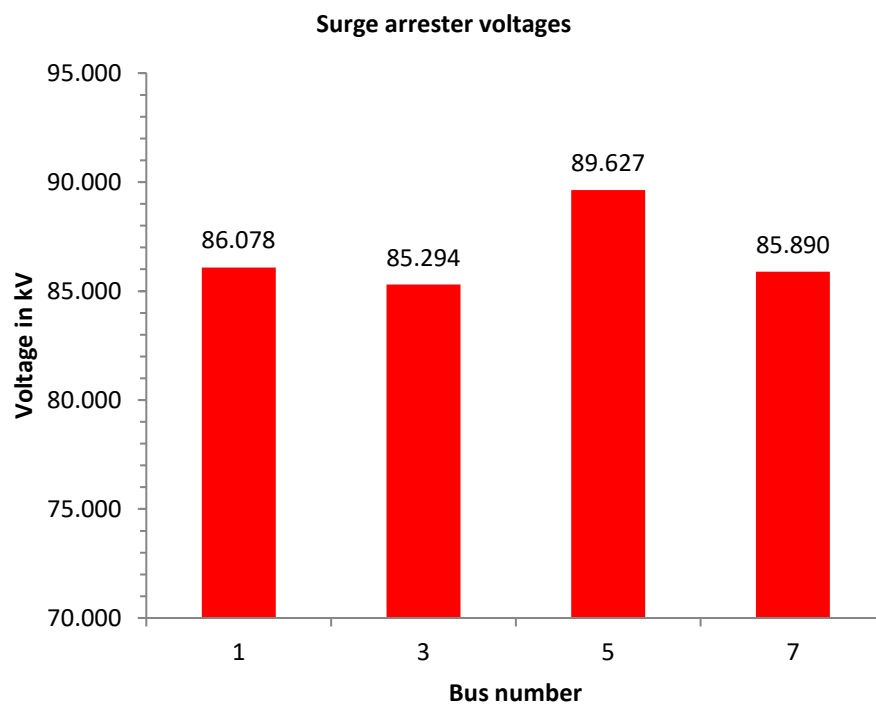


Figure 7:22: Transient voltage magnitudes in the EGTN during a fault at Bloedrivier

The current flowing through the Bloedrivier surge arrester during this transient condition is about 0.6871 A while the rest of surge arresters do not conduct as observed in Figure 7.23.

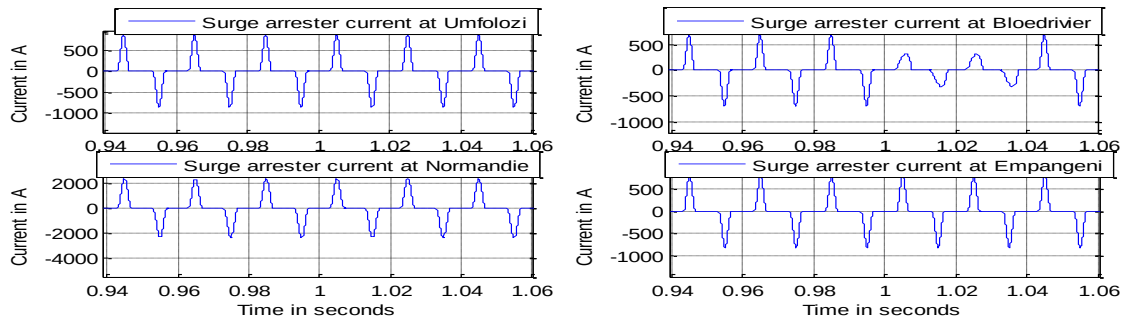


Figure 7:23: Surge arrester current waveforms in the EGTN during a transient fault at Bloedriver

7.3.4 Breaker states for a fault at Normandie at full loading

Normandie breaker opens and closes as expected under this contingency as shown in Figure 7.24.

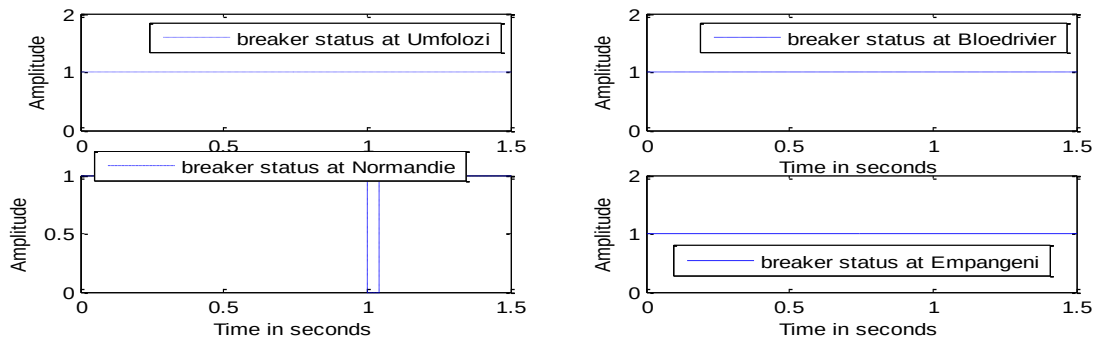


Figure 7:24: Breaker states in the EGTN under a transient fault at Normandie

Surge arrester voltages at buses 1 and 7 are equal (85.989 kV) while the voltage magnitudes at buses 3 and 5 are 84.932 kV and 84.955 kV, respectively as shown in Figure 7.25.

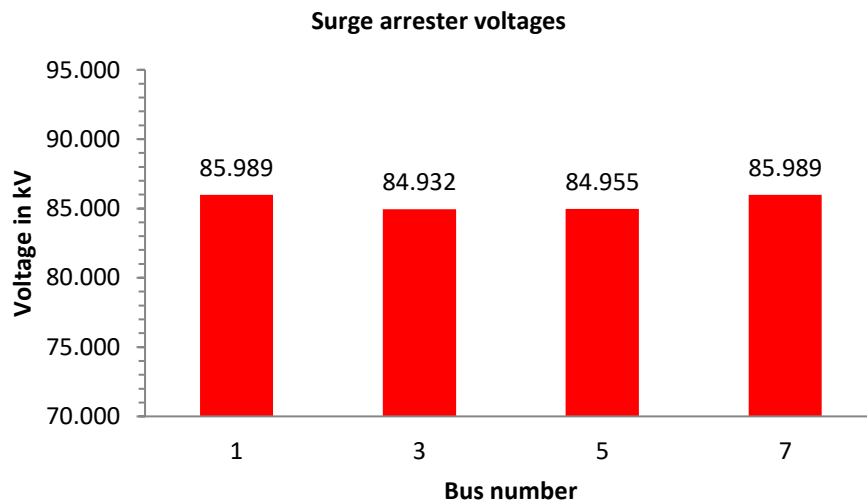


Figure 7:25: Voltage magnitudes in the EGTN for a fault at Normandie

7.3.5 Surge arrester voltage and current waveforms for a fault at Normandie at full loading

Normandie surge arrester clamps the voltage to 0 kV under this contingency as observed in Figure 7.26.

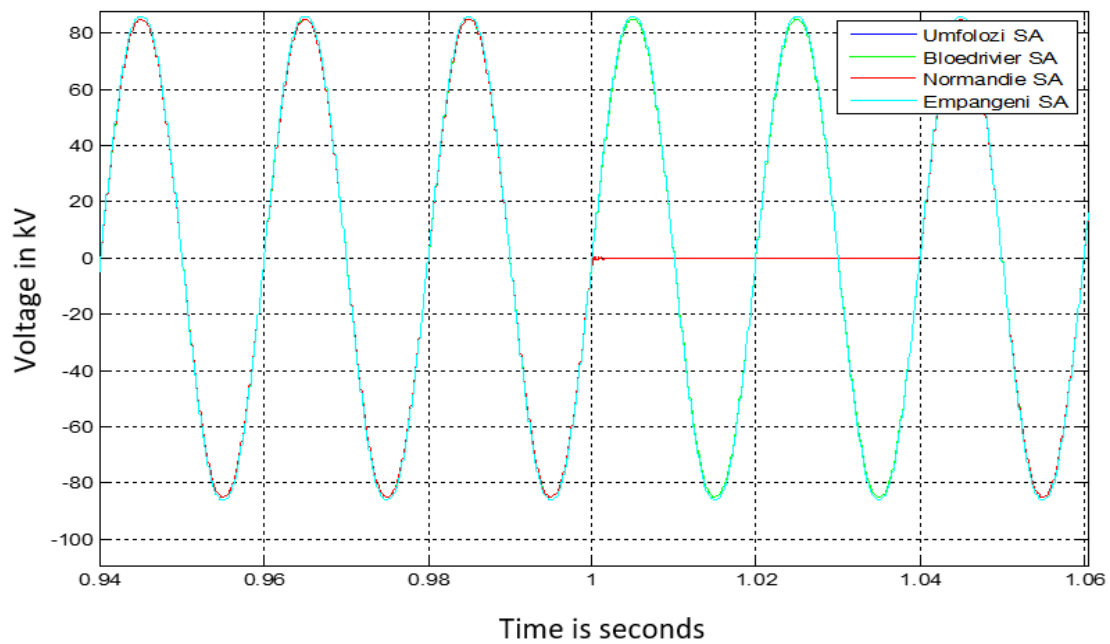


Figure 7:26: Voltage magnitudes in the EGTN for a fault at Normandie

Surge arrester voltages at buses 1 and 7 are equal (85.989 kV) while the voltage magnitudes at buses 3 and 5 are 84.932 kV and 84.955 kV, respectively as shown in Figure 7.27.

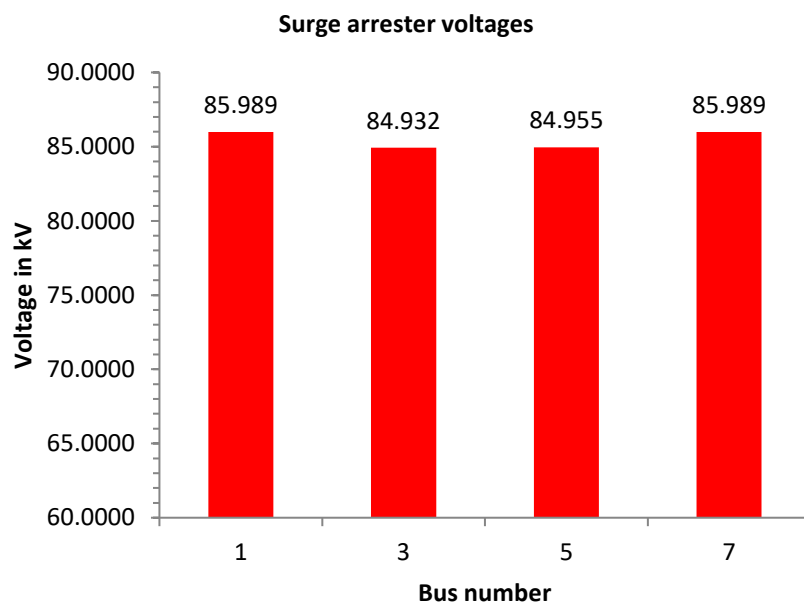


Figure 7:27: Transient voltage magnitudes in the EGTN during a fault at Normandie

No current flows through the Normandie surge arrester under this contingency as shown in Figure 7.28. This is because if a fault occurs at Normandie the impact is much lower because this node is actually the source as seen in Figure 6.6.

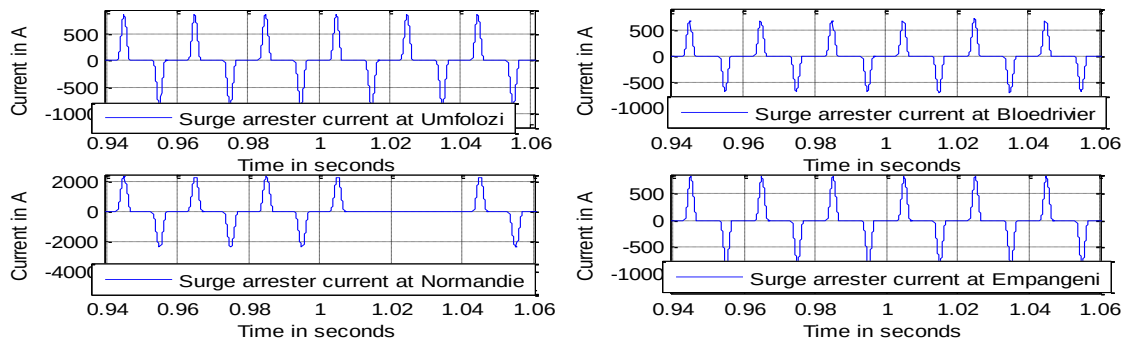


Figure 7:28: Surge arrester current waveforms in the EGTN during a transient fault at Normandie

7.3.6 Breaker states for a fault at Empangeni at full loading

Empangeni breaker opens and closes as expected under this contingency as observed in Figure 7.29.

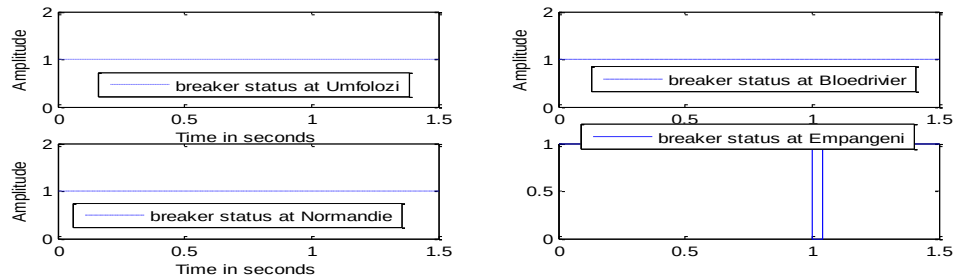


Figure 7:29: Breaker states in the EGTN under a transient fault at Normandie

7.3.7 Surge arrester voltage and current waveforms for a fault at Empangeni at full loading

Empangeni surge arrester clamps the voltage to 0 kV under this contingency as observed in Figure 7.30. This is because the Empangeni node is a much weaker source in the network as shown in Figure 6.6.

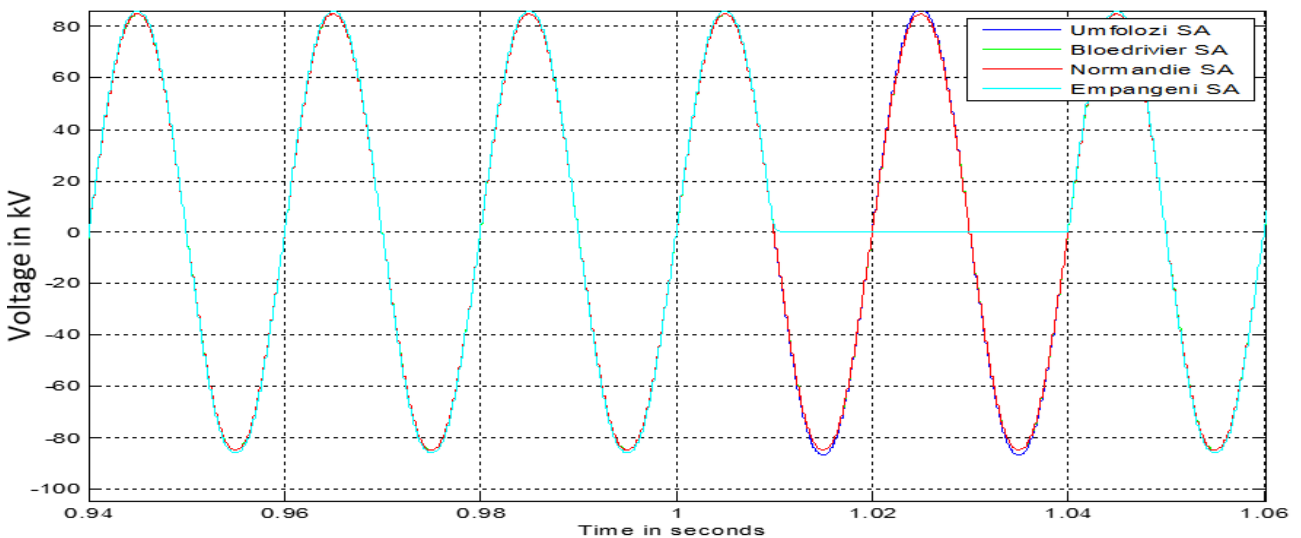


Figure 7:30: Voltage magnitudes seen by surge arresters in the EGTN during a fault at Empangeni

Surge arrester voltages at buses 1 and 7 are equal (85.989 kV) while the voltage magnitudes at buses 3 and 5 are 84.932 kV and 84.955 kV, respectively (Figure 7.31).

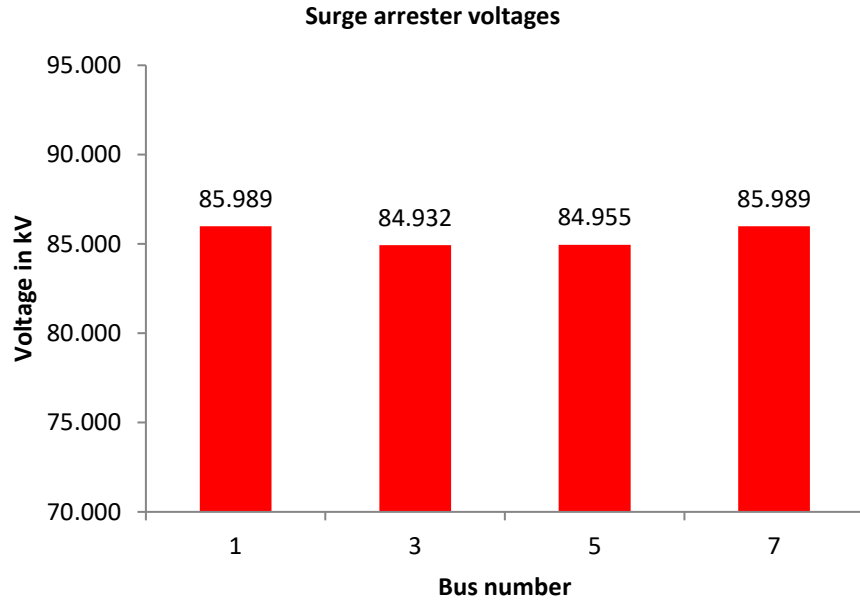


Figure 7:31: Transient voltage magnitudes in the EGTN during a fault at bus 7

No current flows through the Empangeni surge arrester as it conducts under this contingency (Figure 7.32).

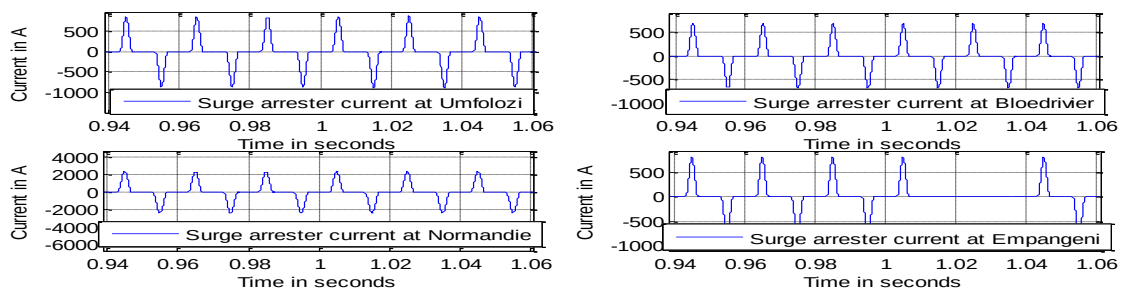


Figure 7:32: Surge arrester current waveforms in the EGTN during a transient fault at Empangeni

7.4 Summary of PSB simulation results under different contingencies

Transient simulation results from under different loading conditions and fault locations namely Umfolozi, Bloedrivier, Normandie and Empangeni respectively in the EGTN are summarized below.

7.4.1 Simulation results for different faults in the EGTN under 0.85pf loading conditions

The following observations are made under different contingencies:

Fault at Umfolozi: Surge arrester voltages at buses 1 and 7 are equal (86.047 kV) while the voltage magnitudes buses 3 and 5 are 85.069 kV and 84.140 kV, respectively. The current flowing through the Umfolozi surge arrester is 0.0408 A under this contingency. This current is less than this surge arrester's discharge current under heavy loading conditions.

Fault at Bloedrivier: Surge arrester voltages at buses 1 and 7 are equal (86.046 kV), while the voltage magnitudes at buses 3 and 5 are 85.068 kV and 85.143 kV, respectively. The current flowing through the Bloedrivier surge arrester is 0.407786 A under this contingency.

Fault at Normandie: Surge arrester voltages at buses 1 and 7 are equal (86.046 kV), while the voltage magnitudes at buses 3 and 5 are 85.071 kV and 85.141 kV, respectively. The current flowing through the Normandie surge arrester is 0.0001 A under this contingency.

Fault at Empangeni: Surge arrester voltages at buses 1 and 7 are equal (86.047 kV), while the voltage magnitudes at buses 3 and 5 are 85.066 kV and 85.140 kV, respectively. The current flowing through the Empangeni surge arrester is 0.0008 A under this contingency.

7.4.2 Simulation results for different faults in the EGTN under 0.7pf loading conditions

Fault at Umfolozi: Surge arrester voltages at buses 1 and 7 are equal (86.084 kV), while the voltage magnitudes at buses 3 and 5 are 85.214 kV and 85.376 kV, respectively. The current flowing through the Umfolozi surge arrester is 0.0044 A under this contingency.

Fault at Bloedrivier: Surge arrester voltages at buses 1 and 7 are equal (86.081 kV), while the voltage magnitudes at buses 3 and 5 are 85.214 kV and 85.373 kV, respectively. The current flowing through Bloedrivier surge arrester is 0.6753 A under this contingency.

Fault at Normandie: Surge arrester voltages at buses 1 and 7 are equal (86.084 kV), while the voltage magnitudes at buses 3 and 5 are 85.213 kV and 85.377 kV, respectively. No current flows through the Normandie surge arrester under this contingency.

Fault at Empangeni: Surge arrester voltages at buses 1 and 7 are equal (86.084 kV), while the voltage magnitudes at buses 3 and 5 are 85.218 kV and 85.376 kV, respectively. No current flows through the Empangeni surge arrester under this contingency.

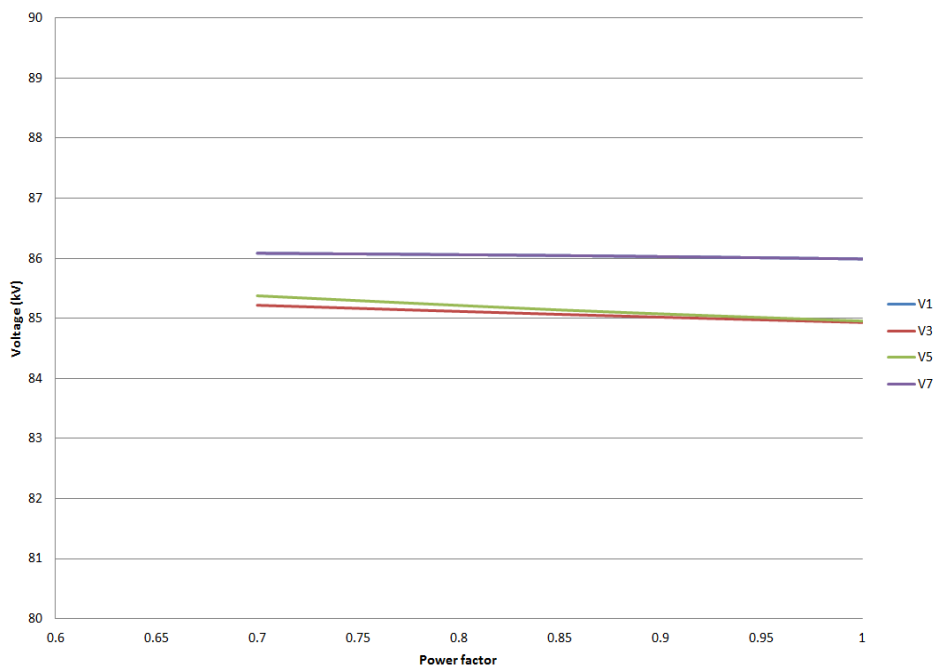


Figure 7.33: Surge arrester voltages for faults at buses 1, 5 and 7

Figure 7.33 indicate that during faults at buses 1, 5 and 7, surge arrester voltages in the EGTN decrease linearly as the power factor increases. These declines occur proportionately to the load because surge arrester voltages are high at light loading at 0.7pf lagging and lower at heavy loading conditions at 1pf lagging. Surge arrester voltages at buses 1 and 7 are the same under these fault conditions as observed in Figure 7.33. The behavior of the Normandie surge arrester voltage is rather erratic under a fault at bus 3 as the load power factor increases from 0.85 to unity lagging. The relationship between voltage and power factor is not linear (Figure 7.34) at

this busbar as the voltage increases drastically during heavy loading conditions. This is due to the position of the Normandie load in the network in relation to generators in the network as shown in Figure 6.6.

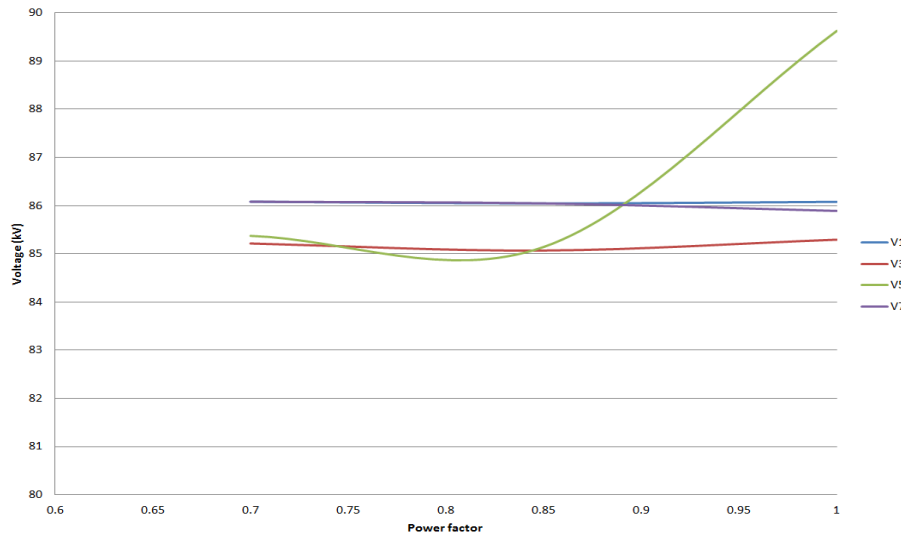


Figure 7:34: Surge arrester voltages for a fault at bus #3

7.5 Performance evaluation of surge arresters in the EGTN model in PSB tool under different loading and fault conditions

Part of the hypothesis in this research is that *when a transient fault occurs at a particular point in the network some surge arrester parameters in the network are exceeded, in particular, the energy absorption capability (EAC)*. Thus, in this section, U_c , I_d , U_r , and EAC parameters of ALL surge arresters are evaluated under different transient fault and loading conditions in the EGTN. These surge arrester parameters are evaluated against technical datasheets (shown in Table B.16) from three suppliers namely ABB, Siemens and Areva.

7.5.1 Parameter evaluation of surge arresters in EGTN for different faults under full loading conditions

Fault at Umfolozi: The U_c , U_r , I_d and EAC parameters of the Umfolozi, Bloedrivier and Empangeni surge arresters are within Eskom and OEMs specified limits as observed in Tables B 17, B 18 and B.20. U_c and U_r parameters of the Normandie surge arrester are within limits while I_d exceeds 1 A and the EAC exceeds ABB class 1-3, Siemens and Areva specified limits in Table B.19.

Fault at Bloedrivier: The U_c , U_r , I_d , and EAC parameters of all surge arresters in the EGTN are within Eskom and OEMs specified limits as indicated in Tables B.21, B.22, B.23 and B.24.

Fault at Normandie: The U_c and U_r parameters of the Umfolozi, Normandie and Empangeni surge arresters are within Eskom and OEMs specified limits while I_d exceeds 1 A. The EAC limits of these surge arresters are exceeded as observed in Tables B.25, B.27 and B.28. The U_c , U_r , I_d , and EAC parameters of the Bloedrivier surge arrester are within limits as indicated in Table B 26.

Fault at Empangeni: The U_c , U_r , I_d , and EAC parameters of the Umfolozi, Bloedrivier and Normandie arresters are within Eskom and OEMs specified limits as indicated in Tables B.29, B.30, B.31 and B.32. The U_c and U_r parameters of the Empangeni surge arrester are within limits while its I_d exceeds 1 A and its EAC exceeds ABB's class 1 and Siemens class 3 specified EAC limits as indicated in Table B.32.

7.5.2 Parameter evaluation of surge arresters in EGTN for different faults under 0.85pf loading conditions

Fault at Umfolozi: The U_c , U_r , I_d , and EAC surge arrester parameters are within Eskom and OEMs specified limits as indicated in Tables B.33, B.34, B.35 and B.36.

Fault at Bloedrivier: Umfolozi, Bloedrivier, Normandie and Empangeni surge arrester performance evaluations for a fault at Bloedrivier show that U_c , U_r , I_d , and EAC parameters are within Eskom and OEMs specified limits as indicated in Tables B.37, B.38, B.39 and B.40.

Fault at Normandie: The U_c and U_r parameters of the Umfolozi, Bloedrivier, Normandie and Empangeni surge arresters are within Eskom and OEMs specified limits as indicated in Table B.41, B.42, B.43 and B.44. I_d and EAC parameters of these surge arresters exceed 1 A and ABB and Siemens specified EAC limits.

Fault at Empangeni: The U_c , U_r , I_d , and EAC parameters are within Eskom and OEMs specified limits as indicated in Table B.45, B.46, B.47 and B.48.

7.5.3 Parameter evaluation of surge arresters in EGTN for different faults under 0.7pf loading conditions

Fault at Umfolozi: The U_c and U_r parameters of the Umfolozi, Bloedrivier, Normandie and Empangeni surge arresters are within Eskom and OEMs specified limits as indicated in Tables B.49, B.50, B.51 and B.52. The I_d and EAC parameters of these surge arresters exceed 1 A and ABB and Siemens specified EAC limits.

Fault at Bloedrivier: The U_c and U_r parameters of the Umfolozi, Bloedrivier, Normandie and Empangeni surge arresters are within Eskom and OEMs specified limits as indicated in Tables B.53, B.54, B.55 and B.56. The I_d and EAC parameters of the Bloedrivier surge arrester exceed 1 A and ABB and Siemens specified EAC limits.

Fault at Normandie: U_c , U_r , I_d , and EAC parameters of the Umfolozi, Bloedrivier, Normandie and Empangeni surge arresters are within Eskom and OEMs specified limits as indicated in Tables B.57, B.58, B.59 and B.60.

Fault at Empangeni: The U_c , U_r , I_d , and EAC parameters of the Umfolozi, Bloedrivier, Normandie and Empangeni surge arresters are within Eskom and OEMs specified limits as indicated in Tables B.61, B.62, B.63 and B.64.

The simulations above show that all U_c and U_r surge arrester parameters in the EGTN remain within the limits specified by Eskom and OEMs under all contingencies. The I_d and EAC parameters of some surge arresters were exceeded under certain contingencies. The EAC of a surge arrester determines whether the surge arrester fails or not, thus surge arresters that had their EACs exceeded under certain contingencies are deemed to have failed. Surge arrester parameter evaluations in the EGTN under different contingencies are summarized in Table 7.1. Surge arresters that can withstand transient faults (marked with tick) and those that failed under fault conditions (marked with X) are indicated in this table. This table also shows that most surge arrester failures occurred under heavy and light loading conditions.

Table 7.1: Summary of surge arrester parameter evaluations in the EGTN under different contingencies

Network loading	Fault location (#)	U_{SA}	B_{SA}	N_{SA}	E_{SA}	MCOV	U_r	I_d	EAC
1pf	1	✓	✓	✗	✓	✓	✓	✗	✗
	3	✓	✓	✓	✓	✓	✓	✓	✓
	5	✗	✓	✗	✗	✓	✓	✗	✗
	7	✓	✓	✓	✗	✓	✓	✗	✗
0.85pf	1	✓	✓	✓	✓	✓	✓	✓	✓
	3	✓	✓	✓	✓	✓	✓	✓	✓
	5	✗	✗	✗	✗	✓	✓	✗	✗
	7	✓	✓	✓	✓	✓	✓	✓	✓
0.7pf	1	✗	✗	✗	✗	✓	✓	✗	✗
	3	✓	✗	✓	✓	✓	✓	✗	✗
	5	✓	✓	✓	✓	✓	✓	✓	✓
	7	✓	✓	✓	✓	✓	✓	✓	✓

7.6 Comparison of surge arrester parameters computed from PSB, PSAT and ATP tools

In this section, the U_c , U_r , I_d and EAC surge arrester parameters of the EGTN computed from each simulation tool under different contingencies are compared.

7.6.1 Comparison of U_c and U_r parameters computed from PSAT and PSB tools

The U_c and U_r parameters computed from PSAT and PSB tools for faults at Umfolozi, Bloedrivier, Normandie and Empangeni under heavy loading conditions are shown in Tables B.65 – Table B.72. These parameters are higher in PSAT than in PSB, but these differences are within tolerable limits (within 10% limit), except for the Bloedrivier and Normandie surge arresters for a fault at Bloedrivier under these contingencies. The I_d and EAC parameters cannot be computed in PSAT.

7.6.2 Comparison of U_c and U_r parameters computed from ATP and PSB tools

The U_c and U_r parameters computed from the ATP and PSB tools for faults at Umfolozi, Bloedrivier, Normandie and Empangeni under heavy loading conditions are shown in Tables B.73, B.75, B.77, B.79, B.81, B.83, B.85 and B.87. These parameters are higher in ATP than in PSB, but these differences are within tolerable limits.

7.6.3 Comparison of I_d parameters computed from ATP and PSB tools

The I_d parameters computed from the ATP and PSB tools for faults at Umfolozi, Bloedrivier, Normandie and Empangeni under heavy loading conditions are shown in Tables B.74, B.78, B.82 and B.86. The I_d parameters computed from ATP are higher than those computed from PSB, but these differences are within tolerable limits.

7.6.4 Comparison of EAC parameters computed from ATP and PSB tools

EAC parameters computed from ATP and PSB tools for faults at Umfolozi, Bloedrivier, Normandie and Empangeni under heavy loading conditions are shown in Tables B.76, B.80, B.84 and B.88. The I_d parameters

computed from ATP are higher than those computed from PSB, but these differences are within tolerable limits.

7.6.5 Comparison of U_c and U_r parameters computed from PSAT and ATP tools

The U_c and U_r parameters computed from PSAT and ATP tools for faults at Umfolozi, Bloedrivier, Normandie and Empangeni under heavy loading conditions are shown in Tables B.89, B.90, B.91, B.92, B.93, B.94, B.95 and B.96. These parameters are higher in the PSAT than in ATP, but these differences are within tolerable limits. I_d and EAC cannot be computed in PSAT, thus these parameters are not compared across PSAT and ATP.

Chapter 8.

Assessing contributing factors in surge arrester failures in the EGTN

In this chapter condition monitoring is done to assess if partial discharges and overheating in surge arrester housing contributed to failures. Quality of supply parameters such as voltage unbalances, regulation and harmonics on the date or around the periods of these failures are also assessed. Surge arrester parameters in the Eskom 88 kV surge arrester specification are also reviewed. These evaluations are used together with simulation results carried out in this work.

8.1 Description of incidents

Network fault incidents are logged in the Eskom's transmission Integrated Plant Performance System (TIPPS) database. Simulation results and information from the voltage recorders are analyzed to determine the causes of surge arrester failures in the EGTN.

Incident 1:

28 October 2009 at 05:04: *“Bloedrivier 1 88 kV line breaker tripped at Umfolozi substation. On investigation it was found that a red phase Areva, model: VARISIL HI 72 surge arrester was damaged and a jumper was broken approximately thirty towers away from Umfolozi substation. The jumper was replaced and the red phase surge arrester was disconnected. There was no interruption of supply to transmission customers”.*

There were no voltage unbalances and regulation at the time of this incident except emissions in voltage harmonics indicated Figure 8.1. However, there are no specific voltage distortions in the EGTN on the date of this incident. PSB and ATP simulations also showed that the energy absorption capability (EAC) of this surge arrester is within limits and the Bloedrivier 88 kV feeder surge arrester does not fail during a transient fault at Umfolozi. A broken conductor and jumper were found 30 towers away from Umfolozi substation during the site inspection of on the day of this incident. This hardware failure would have led to a sustained overvoltage condition in this feeder resulting in the destruction of the white phase surge arrester. This is because in a balanced three phase system when one phase conductor falls to ground the current temporarily flows on the remaining phase conductors. This results in the increase in the voltage on the remaining phase voltages as the current increases due to the fault. This is explained in greater detail by [12] in chapter 24 under internal causes of overvoltages.

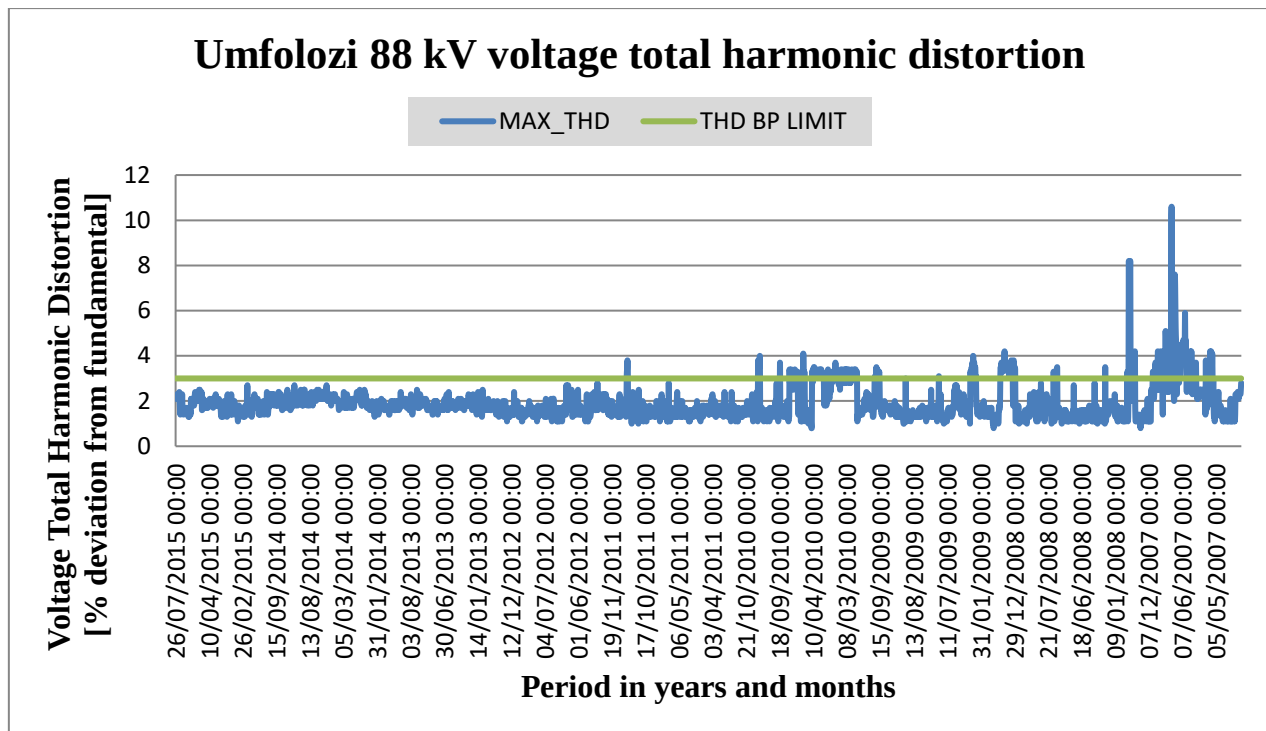


Figure 8:1: Voltage distortions at Umfolozi substation over 8-year period

Incident 2:

16 February 2010 at 14:31: “Empangeni 88 kV line breaker tripped at Umfolozi substation. Control attempted a breaker re-closure at 14:47 but the breaker tripped on closing. Visual inspection at Umfolozi substation showed that the Empangeni white phase Areva, model: VARISIL HI 72 surge arrester had faulted. A red phase broken conductor and a broken jumper were also found on the Umfolozi – Empangeni 88 kV line”.

There were no voltage unbalances, harmonics and regulation at the time of this incident that may have contributed or resulted in this failure. A broken conductor and jumper were found during inspections which would have resulted in an overvoltage condition on the Empangeni 88 kV line leading to the destruction of the white phase surge arrester.

Incident 3:

30 September 2011 at 01:39: “Umfolozi 1 88 kV line breaker tripped at Bloedrivier substation due to a blown red phase Areva, model: VARISIL HI 72 surge arrester. The surge arrester was replaced. There was no interruption of supply to transmission customers”.

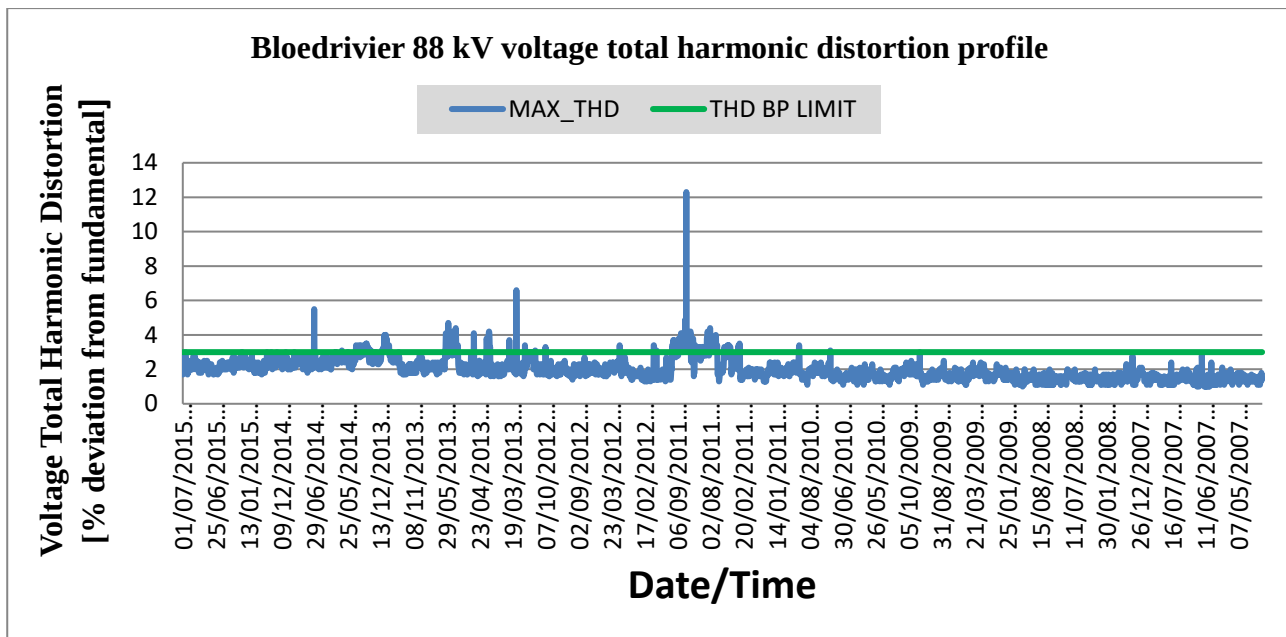


Figure 8.2: Voltage distortions at Bloedrivier substation over 8-year period

There were no voltage unbalances and regulation at the time of this incident except emissions in voltage harmonics indicated Figure 8.2. Figure 8.2 indicates that no voltage distortion was recorded at Bloedrivier substation on this specific date. However, 12.3%, 4.4% and 3.5% voltage THDs were recorded on the 14th of September, 9 July and 3 May in 2011. These harmonics would have contributed to failure of Bloedrivier 88 kV surge arrester failure. A transient fault at Umfolozi (bus 1) resulted in this surge arrester's EAC of 46.8 kJ per kV which is above Areva's EAC limits. This caused the red phase surge arrester to explode.

Incident 4:

22 February 2013 at 02:21: "Umfolozi 1 88 kV line breaker tripped and locked out at Bloedrivier substation due to a red phase Areva, model: VARISIL HI 72 surge arrester that faulted at Umfolozi substation and resulted in an interruption of 9.428 MW for 170.03 minutes ($SM = 0.047 SM$) to traction customers".

There were no voltage unbalances and regulation at the time of this incident except emissions in voltage harmonics as indicated Figure 8.2 indicates that there were no prior significant voltage distortions that may have contributed to this failure. A transient fault at Umfolozi (bus 1) resulted in the Bloedrivier surge arrester EAC of 46.8 kJ per kV. This is above the Areva's surge arrester EAC limits and would have caused this surge arrester to fail. Therefore, there is sufficient evidence that this surge arrester failed due to its EAC limit being exceeded under a transient fault at Umfolozi.

Incident 5:

13 December 2013 at 20:17: "Empangeni 1 88 kV line breaker tripped at Umfolozi due to an insulator failure. On 17 December 2013, during a substation inspection Asea, model: XBC78 surge arresters at Umfolozi were found. On investigation it was found that Control continuously switched this line onto the fault over three days. It is suspected this caused the surge arresters to fail. All three surge arresters were replaced on 18 December 2013. There was no interruption of supply to transmission customers".

There were no voltage unbalances, regulation and harmonics that would have contributed to surge arrester's failure at the time of this incident. A transient fault at Empangeni results in the Umfolozi 88 kV surge arrester absorbing 0.2 kJ/kV which is within EAC limits. However, it was noted during this incident that Eskom network Control continuously switched on the line despite an insulator failure on the Umfolozi – Empangeni 88 kV feeder. This would have led to an overvoltage conditions sufficient to cause an implosion of the Umfolozi surge arrester on this feeder.

Incident 6:

17 February 2014 at 12:34: “Bloedrivier 1 88 kV line breaker tripped and auto-reclosed at Umfolozi substation. Bloedrivier 1 88 kV breaker correctly locked out for the fault but approximately two seconds later the white phase Areva, model: VARISIL HI 72 surge arrester at Umfolozi failed catastrophically resulting in an interruption of 10.764 MW for 88.67 minutes ($SM = 0.028SM$) to traction customers. A broken jumper was also found on the Skume Tee off”.

There were no voltage unbalances, regulation and harmonics at the time of this incident. Transient simulations above showed that a transient fault at Bloedrivier results in the Umfolozi surge arrester absorbing 13.4 kJ/kV of energy. However, the Areva surge arrester EACs are not specified in the datasheets, however is sufficient probable cause that a transient fault at Bloedrivier would have resulted in the Umfolozi surge arrester failure.

8.2 Evaluation of the EGTN surge arrester’s infrared scans reports and metallurgy report.

In this section in-service conditions that may have contributed to the surge arrester failure incidents in the EGTN are analyzed.

8.2.1 Analysis of surge arrester infrared scans

Infrared scans are one of the useful plant condition assessment tools as they can detect abnormal heat patterns in electrical connectors, switchgear components, bushings, surge arresters etc. The heat differential, ΔT of the equipment can be derived from heat differentials of similar plant or from the ambient temperature of 22° Celsius [78]. The detection of abnormal heat patterns requires thermal images to be taken during peak loading condition. Peak loading conditions in the EGTN occur between 04h00 – 07h00 and 15h00 – 20h00 thus abnormal heat patterns detected during these periods allow the plant manager to make necessary operational decisions such as switching suspected equipment out of service until defect(s) are cleared.

In this section, infrared scans of surge arresters at Umfolozi and Bloedrivier substations are examined. This is done to assess if there were any abnormal heat patterns prior to the failures of surge arresters in incidents 1-6 above. All spot temperature namely sp1, sp2 and sp3 were taken at an ambient temperature of 20°C and within 3m away from the surge arrester. The following surge arrester infrared scans were taken at Umfolozi and Bloedrivier substations for analysis:

- Umfolozi-Empangeni 88 kV surge arresters (26 August 2015, 19:08)
- Umfolozi - Bloedrivier 88 kV surge arresters (26 August 2015, 19:20)
- Bloedrivier – Normandie 88 kV surge arresters (27 August 2015, 07:12)
- Bloedrivier – Umfolozi 88 kV surge arresters (27 August 2015, 07:04)

Figures D.1-D.12 in Appendix D indicate that these surge arresters did not show any signs of excessive heat during peak loading conditions as all spot temperatures are within the 50°C thermal limit stipulated in [78]. There is no evidence that excessive or abnormal heat contributed to surge arrester failures in the EGTN.

8.2.2 Analysis of metallurgy report for samples taken to the Eskom’s testing centre

Due to the high number of Areva surge arresters that failed in the EGTN, budget constraints and laboratory backlogs, only the Umfolozi- Bloedrivier 88kV feeder Areva surge arrester that failed on the 17 February 2014 at 12:34 (shown in Figure D.12) was sent to Eskom’s Research, Testing and Development (R, T and D) laboratory for analysis.

The purpose of the examination was to assess if surge arresters from this manufacturer could be failing due to moisture ingress and/or failure in the sealing system. The investigations made in [78] and observations made in Figures D.13 – D.15 show that:

- The surfaces of bottom end caps in contact with the surge arrester’s base plate were rusted (Figure D.14(a)). However, there were no signs of corrosion on the connectors to the conductors at the top (Figure D.14(b)), therefore there is no evidence that these surge arresters could have failed due to corrosion.

- The outer and inner seal pulled away from each other as indicated by the yellow dots in Figure D.15(b). However, it could not be determined if the delamination of these seals occurred prior to, or after the failure. There is no evidence that the inner seal had pulled away from the end cap as no discoloration or corrosion products were noticed in the inner seal and aluminum end cap interface which could suggest the possibility of moisture ingress.
- There were also no signs of corrosion in the seal interfaces (Figure D.15(b)). There is no evidence that this surge arrester failed due to moisture ingress i.e., there is no evidence that the sealing system failed.

8.3 Evaluation of the Eskom 88 kV surge arrester specification

Manufacturers design equipment to meet customer needs by adhering to customer equipment specifications. Errors in specifications provided by customers to manufacturers often lead to incorrect and/or insufficient equipment designs resulting in failures. The following inconsistencies and errors were noted in the Eskom surge arrester specification:

Surge arrester residual voltage parameter

Eskom specifies a residual voltage, U_{res} of 210 kV at 10 kA, 8/20 μ s standard voltage waveform for 88 kV surge arresters. The surge arrester's residual voltage is a function of the discharge current across the surge arrester terminals as it conducts. The discharge current is dependent on the dimensions of the metal oxide blocks and the transient voltage. The latter is not readily known hence it is difficult to substantiate the specification of the U_{res} of 210 kV. Residual voltage is a product of discharge current (during the arrester conduction) and terminal voltages. This voltage drop is also dependent on other environmental factors such as pollution, therefore it should be specified to manufacturers. If residual voltages are to be specified, they must be based on transient studies.

Surge arrester dimensioning and sizing

A minimum diameter of 26 mm in the MO block is specified in the Eskom 88 kV surge arrester specification without substantiation. These blocks are tested in routine duty cycle tests as per requirements in IEC 60099-4 and can be witnessed by utilities as part of factory acceptance tests. Specifying these unintentionally changes an already specified U_{res} parameter. The specification of 26 mm metal oxide block further complicates the manufacturer's compliance to the specification as there is no room for adjustment in the dimensioning. It is impractical for manufacturers to design for an exact U_{res} value with an exact MO block diameter. It is safer not to specify this parameter but rather put it under factory acceptance tests (FAT) items. A basic insulation level (BIL) value of 380 kV is specified by Eskom whilst at the same time the U_{res} value of 210 kV is specified. This increase in the BIL level increases the safety margin of 1.25 to 1.8 and results in a bulky surge arrester. Specifying these requirements cause manufacturers to re-dimension MO blocks resulting in expensive surge arresters as more materials are used.

Surge arrester's continuous voltage and rated voltage parameters

A voltage regulation of 10% is used for U_c calculations in the Eskom 88 kV surge arrester specification yet a 1.05 pu value is used to calculate U_c values. This leads to incorrect and inconsistent calculations by manufacturers. The correct value should be 10% (1.10 pu) as per NRS-048 voltage limits for 88 kV systems. The surge arrester rated voltage, U_r , is not specified in the Eskom's surge arrester specification. This is a critical parameter for manufacturers as safety margins are required for the prevention of direct equipment strikes. U_r parameter is directly proportional to the surge arrester's continuous operating voltage, U_c . Safety margins or ground factor of 25% for solidly grounded four wire three phase systems are stipulated in [3]. Thus, the minimum U_r value for an 88 kV surge arrester should be specified as $67 \text{ kV} \approx \frac{1.25 \times 88 \times 1.05}{\sqrt{3}}$.

Classification of surge arresters

Eskom's specification refers to table 1 of the IEC 60099-4 for the classification of surge arresters and stipulate minimum nameplate data display. This may lead to incorrect surge arrester selections especially for

applications where nominal discharge currents cut across distribution and transmission “duty” designations. The correct surge arrester designations must be reflected in the name plate.

Calculation errors in surge arrester parameters and ambiguities in IEEE and IEC terminology

Power system voltages are classified as either IEEE or IEC system voltages and Eskom’s power system classification follows the IEC power system classification, hence the IEC 60099-4:2014 surge arrester standard is adopted. Surge arrester MCOV parameters are used for IEEE classified power systems whilst U_c values are used for IEC classified power systems [11]. The Eskom surge arrester specification treats MCOV and U_c values as the same parameter which is incorrect and leads to confusions for manufacturers as they would follow IEC standards whereas IEEE values are specified.

These ambiguities lead to calculation errors. For example, the U_c value of 56 kV specified by Eskom to OEMs for 88 kV surge arresters is low because the maximum rated voltage (U_m) of the IEC 88kV system is 97 kV. Therefore, an 88 kV surge arrester withstand voltage should be 59 kV ($\approx \frac{97\text{kV} \times 1.05}{\sqrt{3}}$). These errors in calculations lead to incorrect surge arrester energy absorption capabilities as these parameters are evaluated in terms of MCOV or U_c values with different results and meaning. Ultimately, these calculation errors lead to incorrect surge arrester selections by Eskom.

There are inconsistencies in the usage of rated voltages, U_r , and continuous voltages, U_c , in the evaluation of surge arrester thermal energy rating, W_{th} , in the Eskom 88 kV surge arrester specification. The IEC thermal rating definition of the surge arrester specifies U_r to be used in the evaluation of the surge arrester energy absorption capability. It was noted in this dissertation that different manufacturers use either U_r or U_c values in evaluating this parameter. These U_r and U_c values are different with U_r being a 1.25 multiple of U_c , where 1.25 is the ground factor of solidly grounded four wire systems as it is the case with the EGTN. A ground factor of 1.25 is not specified in the Eskom 88 kV surge arrester specification, therefore rated voltages may not be fully understood by manufacturers.

Surge arrester switching impulses

The Eskom 88 kV surge arrester specification specifies 88 kV class 2 surge arresters for 100 kA, 8/10 μ s switching impulses. This impulse is for lightning surge arresters and not for line or station surge arresters. The 8/10 μ s time ratio is much shorter and does not fully cater for surges with longer tail waves and more dangerous to the surge arrester and other equipment. These switching impulses should be specified as 10 kA, 8/20 μ s for distribution surge arresters and 20 kA, 8/20 μ s for station surge arresters as per Table 1 in IEC 60099-4:2014 surge arrester standard.

Impact of power system temporal overvoltages on surge arrester’s cooling times

The Eskom 88 kV surge arrester specification does not consider network temporary overvoltages (TOVs). Although temporary overvoltages are also not explicitly defined in the IEC 60099-4 surge arrester, these overvoltages may last for several minutes in the power system. Therefore, surge arrester cooling times should be sufficiently specified. The Eskom 88 kV surge arrester specification specifies a cooling time of three minutes which may be short for traction loads.

Chapter 9.

9.1 Conclusions and future work

This research highlighted adverse impacts of poorly selected surge arresters in the power system's insulation coordination and reliability. This required transient studies in evaluating important parameters in surge arrester performance and selections. This was done by modelling, simulating the EGTN under different contingencies and computing important surge arrester parameters. The evaluation of these parameters against parameters provided by surge arrester manufacturers enabled surge arrester performance evaluations. This evaluation and transient studies carried out in this work will assist in surge arrester performance evaluations and selections during network planning and design stages. EACs and discharge currents were found to be the most important surge arrester parameters in the selection of surge arresters. In order to evaluate the impact of surge arrester failures in the EGTN the reliability evaluation of the network was done. However, different reliability indices are used in the reliability evaluation of Eskom transmission and distribution networks.

This meant that neither divisions could accurately quantify the impact of the failures on the reliability of either network. This was addressed by applying analytical and simulation methods in the reliability evaluations of the EGTN. This was done by applying the MATLAB simulation code proposed by Shavuka et al. [1] in computing common reliability indices of the EGTN. Comparisons in reliability indices between these networks were made. This allowed reliability indices to be standardized between these networks. This research was mainly inquisitorial and focused on investigating causes into surge arrester failures in the EGTN. This required that other contributing factors that may lead to surge arresters failing be investigated. These factors include the review of the Eskom 88 kV surge arrester specification, the condition monitoring of surge arresters in this network by studying infra-red scans, the evaluation of laboratory results of the sample surge arrester and the impact of quality of supply emissions around periods of these failures.

Inconsistencies in surge arrester parameter specifications and inaccuracies in the terminology usage between IEC and IEEE classified systems were noted in the Eskom 88 kV surge arrester specification during its review. These deficiencies were found to have led to poor surge arrester selections in the EGTN and resulted in surge arrester failures that now experienced in this network. There were no in-service conditions that were found to have contributed to surge arrester failures in the EGTN. A number of voltage harmonics were noted around the periods when these failures occurred which may have contributed to these failures. Laboratory results did not indicate any signs of moisture ingress into the faulted surge arrester and there were signs of mechanical fatigue.

The PSB tool was used as the primary simulation tool in this study as it was necessary to understand the behavior of the EGTN under easily diagnosable physical properties of the network. Important surge arrester parameters were successfully computed in this tool and compared with parameters provided by manufacturers and those specified by Eskom. The speed and accuracy of the PSB tool in modelling and simulating this network and computation of surge arrester parameters were evaluated by comparing this tool with PSAT and ATP tools. The PSAT was found to be useful for transient studies in this network however, this tool does not have surge arrester models requiring user defined surge arrester models which are time consuming. The ATP tool was found to be superior due to its modelling capability, computational speed and accuracy. However, this tool requires parameters which are not readily available such as tower mechanical and electrical parameters. Findings and conclusions made in this research are summarized below.

9.2 Answers to research questions

The hypothesis that was to be tested in this research was stated as:

“Fast transients on traction systems initiate system faults that can be reduced by suitable insulation coordination through transient analysis to improve surge arrester performance evaluations, selections and improved system reliability at acceptable cost”

The literature review, investigations conducted and observations made in the course of this study can provide the following answers to the research questions posed in chapter 1.

Question 1: What is the process by which fast transients cause faults? How can the EGTN be modelled, simulated and analyzed to evaluate the impact of these transients on surge arrester performances?

Transient faults in the power system are caused by very fast faults usually in the order of milliseconds and can remain in the system for several minutes. These faults can also be caused by normal operations such as the closing and opening of breakers. Transient faults in the power network result in voltage surges due to the change in the power flow. These surges are small deviations in steady state and transient state voltages in the power system. Findings from this research indicate that some of these transient faults lead to overvoltage conditions in the network. These overvoltages have adverse impacts on the performance of surge arresters in the network and can result in their failures. This study found that the lack of transient studies and surge arrester performance evaluations during the planning and design of the network result in poor surge arrester selections. Surge arrester performance evaluations require that surge arrester parameters are assessed for suitability before surge arrester selections. This requires that the network is modelled and surge arrester parameters computed and assessed. This was done in this study by modelling and simulating the East Grid Traction Network (EGTN) by initiating fast breaker operations under different loading conditions at various nodes in the network and assessing surge arrester parameters. This was done by using Power System Blockset (PSB), Power System Analysis Toolbox (PSAT) and Alternate Transient Program (ATP) simulation tools and modelling traction loads as variable loads with power factors of 0.7pf, 0.85pf and 1pf lagging. Faults were initiated sequentially at a specific time (1.0 second) and at buses where surge arresters are installed, and the fault was set to clear at 1.04 seconds. The power flow was run and computed busbar voltages under transient state conditions were compared with those in steady state conditions to assess surge arrester parameters. Continuous operating voltage (U_c), rated voltage (U_r), discharge current (I_d) and energy absorption capability (EAC) surge arrester parameters were found to be the important surge parameters in surge arrester performance evaluations during the literature review in this study. The evaluation of surge arrester parameters was done by comparing computed surge arrester parameters in the EGTN after transient faults with those parameters provided by manufacturers. It was found that a number of I_d and EAC limits were observed under low loading conditions (0.7pf lagging) and heavy loading (1pf lagging) conditions causing some surge arresters in the EGTN to fail as shown in Table 7.1. I_d and EAC were found to be the most important surge arrester parameters in the energy withstand capability of a surge arrester in the network under trainset conditions.

Question 2: What methods can be used to evaluate the reliability of the network and what tools can be used to achieve this?

In Eskom transmission reliability indices such as systems minutes (SM), number of interruptions (NOI), circuit availability index, circuit unavailability index are used. Eskom distribution uses common reliability indices such as System Average Interruption Duration Index (SAIDI), System Average Interruption Frequency Index (SAIFI), Average System Availability Index (ASAI) and Average System Unavailability Index (ASUI). The computation of these indices can be done by using analytical and simulation network reliability evaluation methods. The former uses actual network physical properties using network failure modes and effects analysis (FMEA) to compute reliability indices. The latter uses Monte Carlos simulations to compute reliability indices. In this study the analytical method was done by representing the EGTN in Roy Billinton Test System (RBTs) format and empirically computing its reliability indices. The simulation method was done by applying and modifying the MATLAB code proposed by Shavuka et al. In this study the analytical method was useful in understanding how to arrive at each reliability index. However, this method was found to be cumbersome and slow in computing reliability indices when the size of the network increases. The simulation method was found to be faster in computing reliability indices especially for larger networks. However, its accuracy relies on a high number of iterations/simulations.

Question 3: How can transient simulation results be used to improve surge arrester performance and surge arrester selections?

Eskom currently does not use transient studies to ascertain if surge arresters will withstand network stresses brought about transient. This is problematic when dealing with traction loads which are dynamic, exhibit negative sequences and highly dynamic. Transient studies are critical in assessing the suitability of surge arresters in the power grid, distribution loads and traction loads. In this study transient simulation

results enabled the performance evaluation of surge arrester after transient faults in the network. This resulted in the evaluation of surge arrester parameters under each contingency by comparing each surge arrester parameter with those parameters provided by manufacturers. This determined whether each surge arrester in the network can withstand stresses brought about transient faults. These surge arrester evaluations will lead to the accurate selection of surge arresters in the network and/or before new surge arresters are installed after failures. This study also found that transient simulations assists in improving surge arrester specification. This is because a number inconsistencies in the terminology usage for IEC and IEEE classified power systems were noted during the review of the Eskom 88 kV surge arrester specification. For example, maximum continuous operating voltages (MCOV) designated for IEEE classified power systems are used in the specification instead of continuous operating system (U_c). Inaccuracies and ambiguities were also noted in specification where critical surge arrester EACs are specified using residual voltages instead of rated voltages or continuous voltages. Residual voltages are also specified in the specification although they depend on the number of metal oxides and the length of the surge arrester's housing which are not known until design stage. These inaccuracies and ambiguities will only lead to confusion for manufacturers and lead to poor surge arrester performance evaluations and selections and ultimately surge arrester failures in future.

Question 4: Does the application of reliability methods and improved surge arrester selections lead to improved insulation coordination of this network?

Yes. Reliability indices used by Eskom transmission are different from those reliability indices used by Eskom distribution. This creates a problem in assessing the impact of Eskom transmission surge arrester failures on Eskom distribution networks. Applying reliability indices in the EGTN allowed the computation of reliability indices in each division and comparing these indices for similarities. For instance, this study found that reliability indices such as SAIDI, SAIFI, ASAI and ASUI used in Eskom distribution division are similar to reliability indices such as SM, NOI, circuit availability index and circuit unavailability index respectively used in Eskom transmission division. This allows the standardization of reliability indices between these divisions and enables a comprehensive evaluation of the impact that surge arrester failures have on the reliability of both Eskom transmission and distribution networks.

Question 5: Will improved surge arrester selections and insulation coordination increase costs and is the benefit worth the extra cost?

Yes. Improved surge arrester installations will ensure that surge arresters are able to withstand voltage surges in the network. The prevention of surge arrester failures will ensure that the power system's insulation coordination is optimal. This will protect critical and expensive power system components such as instrument transformers, powerline hardware such as insulators, through faults in power transformers and protection system's maloperations against dangerous overvoltages.

9.3 Research hypothesis validation and research findings

The hypothesis as stated in the beginning of this dissertation was, ***“fast transients on traction systems initiate system faults that can be reduced by suitable insulation coordination through transient analysis to improve surge arrester performance evaluations, selections and improved system reliability at acceptable cost”***

Studies undertaken to test this hypothesis have shown it to be valid. This is because modelling the EGTN and initiating transient faults in this network enabled the computation of surge arrester parameters. The evaluation of these parameters improves surge arrester selections and assists in preventing surge arrester failures. This ensure optima insulation coordination and improves network reliability at an acceptable cost.

This work showed that transient simulations are critical in surge arrester performance evaluations and selections during network planning and design stages. Surge arrester discharge currents and energy absorption capabilities were found to be important parameters in assessing the suitability of surge arresters in the network. This study found a number of inconsistencies in Eskom's 88 kV surge arrester specification, inconsistencies in terminology usage between IEEE and IEC classified systems. These inconsistencies and the lack of transient studies also lead to incorrect surge arrester selection in the network. This is due to errors in surge arrester parameter calculations and surge arrester selections. This compromised the grid's insulation coordination as

evident in the high number of surge arrester failures experienced in the EGTN. This study showed that it is critical to simulate the network for surge arrester parameter evaluations. This forms part of important inputs surge arrester performance evaluations and selections. This task can also be done prior to the installation of new surge arresters or replacements in already existing networks. This can be achieved by computing surge modeling and simulating the network by utilizing PSB, PSAT and ATP simulations tools.

The PSB tool was found to provide a simple and accurate diagnosis of voltage surges in the network. However, the computation time in this tool becomes quite long as the network expands. PSAT tool is useful as has a number test files that can be modified to match the topology of the network to be simulated and it is quite fast. However, surge arrester models must be constructed using user defined functions. This can be quite cumbersome and time consuming if the network is large. ATP tool was found to be very good as it is accurate, possess a broader library including different surge arrester models and requires shorter computation times. However, this tool requires a lot of data inputs such as tower design parameters that are not readily available, especially for older networks where design drawings do not exist.

In this study the MATLAB simulation code proposed by Shavuka et al. [1] was extended to 88 kV networks and traction networks is capable in computing common power system reliability indices. This is because reliability indices computed from this code were found to be comparable reliability indices computed from this from the analytical method. The standardization reliability indices used in reliability evaluation of transmission and distribution networks is possible. This is because this study found that Eskom transmission's reliability indices such as SM, NOI, circuit availability index and circuit unavailability index are similar to Eskom distribution's reliability indices such as SAIDI, SAIFI, ASAI and ASUI respectively.

9.4 Implications of the research findings

The work carried out in this research has following implications:

- *Review of the Eskom 88kV surge arrester specification*
Equipment specifications are important documents when utilities and manufacturers enter into business and contractual obligations. In the course of this study a number of deficiencies were noted in the Eskom 88 kV surge arrester specification. There is a need for Eskom to review this specification to ensure that surge arresters are correctly selected. This will prevent future surge arrester failures and financial losses incurred by Eskom due to untimely surge arrester failures.
- *Costs that will be incurred by Eskom in the replacement of surge arresters in the EGTN*
Some surge arresters were found to be unsuitable in the EGTN and need to be replaced. This decision involves assessing the financial implications for Eskom as projects are undertaken based on their financial viability. Hence project's net present value (NPV), discounted payback period and internal rate (IRR) of return financial parameters are evaluated as shown in Table C.2. In the event that Eskom opts for the replacement of surge arresters in the EGTN, the selection guide in Figure C.1 should be followed. The financial evaluation in Table C.2 is based on, (i) a unit cost of R8,484 for a normal 88 kV surge arrester in year 2015. It is estimated that the unit cost of a high energy rating surge arrester is about 40% higher based on quotations received from three suppliers. The unit cost adjustment to 2018 Rands is 10% per annum, hence the 2018-unit cost of a surge arrester is about R13,526 as shown in the evaluation. (ii) Other costs such as engineering costs, project management costs, etc., in the overall financial assessment of the project. (iii) A 10% rate of return utilized in the financial evaluation if 88 kV surge arresters in the EGTN are to be replaced. This rate of return is subject to South African interest rate fluctuations as published periodically by the SARB. In the event that surge arresters in the EGTN are replaced as per recommendations, Eskom East Grid Transmission will have to budget a minimum of R2,943,615 for the replacement project. The scope of the project will be to replace 39× 88 kV surge arresters at Umfolozi, Bloedrivier, Normandie and Empangeni substations as shown in Table C.2. An investment of R2,943,615 is viable for Eskom as the project's net present value is positive and the project's internal rate of return is greater than the required return on investment by about 9%. An investment of R2,943,615 is much lower in comparison to the overall cost of unserved energy on 88 kV feeders in the EGTN; this makes this investment justifiable. Further, this investment amount is small in comparison to the loss of revenue caused by surge arrester failures in this network

and financial losses incurred by Transnet (Spoornet), which are estimated to be in tens of millions of Rands when these feeders are on forced outage. It can be observed by inspection that the discounted payback period of this project is about twelve years and six months (12.5 years). This project would start generating profit from the 13th year (year 2031) onwards with profits doubling in the 16th (year 2034). Further savings in engineering costs, project management costs and labour costs can be achieved if this project is executed in-house depending on human capital and capacity.

- *Standardization of reliability evaluation methodologies in Eskom*
Impacts that surge arrester failures in transmission networks have in distribution networks is contested within the Eskom business. This is because different reliability indices are used by each division. There is a need for uniform reliability indices between transmission and distribution systems. This will assist in ensuring that common reliability indices are used in evaluating the impact of faults caused by either network.
- *Inclusion of tower parameters in ATP tool for improved surge arrester performance evaluations*
Although the ATP tool was found to be the most efficient and faster simulation tool, however, its accuracy hinges on the quality of tower modelling. This requires an evaluation of different tower designs for improved power transfer capability. This will further improve the accuracy of simulation results.
- *Improving traction simulation models by considering the impact of quality of supply emissions*
The primary aim of this work was to model, simulate and evaluate surge arrester parameters when transient faults occur in other busbars in the network. In this work, several models are proposed for PSB, PSAT and ATP tools as detailed in chapter 7 and conference papers [79, 75] published in the course of this work. There is scope for the improvement of the models for higher accuracy which will require that proposed models in this work be expanded to allow for the simulation and evaluation of the voltage unbalances. The simulation model proposed by Ojo et al. [80] promises greater improvements in these models and accuracy as it considers the impact of voltage unbalances.
- *Development of user-defined surge arrester functions in PSAT tool for transient simulations*
The work done in this research indicated a need for the design and testing of auxiliary devices such as surge arresters in this tool. This will ensure that surge arrester parameters are computed quicker without using empirical mathematical manipulation in the computation of continuous operating voltage and rated voltage parameters. User defined surge arrester models in this tool also require precise surge arrester parameters which are not readily available.

9.5 Concluding remarks and final thoughts

The investigation of 88 kV surge arresters in the EGTN has been successful as this network was modelled and simulated to compute important surge arrester parameters. This was achieved by using PSB, PSAT and ATP tools in the computation of these parameters. This study showed that transient studies are critical in surge arrester performance evaluations and selections. The evaluation of surge arrester parameters in this network also highlighted the importance of accurate equipment specifications. This will prevent surge arrester failures, improve the reliability of the network and ensure customer satisfaction.

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Appendix A

Table A. 1 Suggested continuous voltages for IEC Systems

Typical IEC System Voltages			Suggested Uc for IEC Systems		
Nominal Line to Line Voltage	Typical Max Line to Line Voltage	Max Line to Grnd Voltage	Solidly Earthed Neutral at the Source Transformer	Impedance Earthed, Isolated and Delta Systems	Transmission Line Arresters for Lightning Protection Only
kV rms	kV rms	kV rms	Uc	Uc	
3.3	3.7	2.1	2.4	4.0	
6.6	7.3	4.2	4.8	7.2	
10.0	11.5	6.6	7.2	12	
11.0	12.0	6.9	9.6	12	12
16.4	18.0	10.4	12	18	18
22.0	24.0	13.9	16.8-24	24	24
33.0	36.3	21.0	24-36	36	36
47.0	52	30.1	33-43	53	43-53
66.0	72	41.6	43-58	72	58-72
91.0	100	57.8	66-77	102	77-102
110	123	71.1	77-86	125	86-125
132	145	83.8	96-115	145	115-145
155	170	98.3	110-125	170	125-170
220	245	142	154-188	245	188-245
275	300	173	182-192	300	192-300
330	362	209	221-230	360	230-360
400	420	243	269-288	420	288-420
500	550	318	420-440	550	440-550

Table A. 2 Power system voltage classifications in IEC and IEEE

System RMS Voltages in kV	IEEE [11]							
Nominal line to line	8.32	12.50	27.60	34.50	46.00	69.00	115.00	138.00
Maximum line to line	8.74	13.10	29.00	36.20	48.30	72.50	121.00	145.00
Maximum line to ground	5.05	7.57	16.80	20.90	27.90	41.90	69.80	83.80
Minimum MCOV	5.05	7.57	16.80	20.90	27.90	41.90	69.80	83.80
	IEC [11]							
Nominal line to line	10.00	11.00	16.40	47.00	66.00	91.00	110.00	132.00
Maximum line to line	11.50	18.00	18.00	52.00	72.00	100.00	123.00	145.00
Maximum line to ground	6.60	10.40	6.90	30.10	41.60	57.80	71.10	83.80
Minimum U_c	6.60	10.40	13.90	21.00	41.60	57.80	71.10	83.80
	Eskom [3]							
Nominal line to line	11.00	22.00	33.00	44.00	66.00	88.00	132.00	220.00
Maximum line to line	12.00	24.00	36.00	48.00	72.00	100.00	145.00	245.00
Maximum line to ground	6.35	12.70	19.05	25.40	38.11	50.81	76.21	127.02
Minimum MCOV or U_c	6.99	13.97	20.96	27.94	41.92	55.89	83.83	133.37

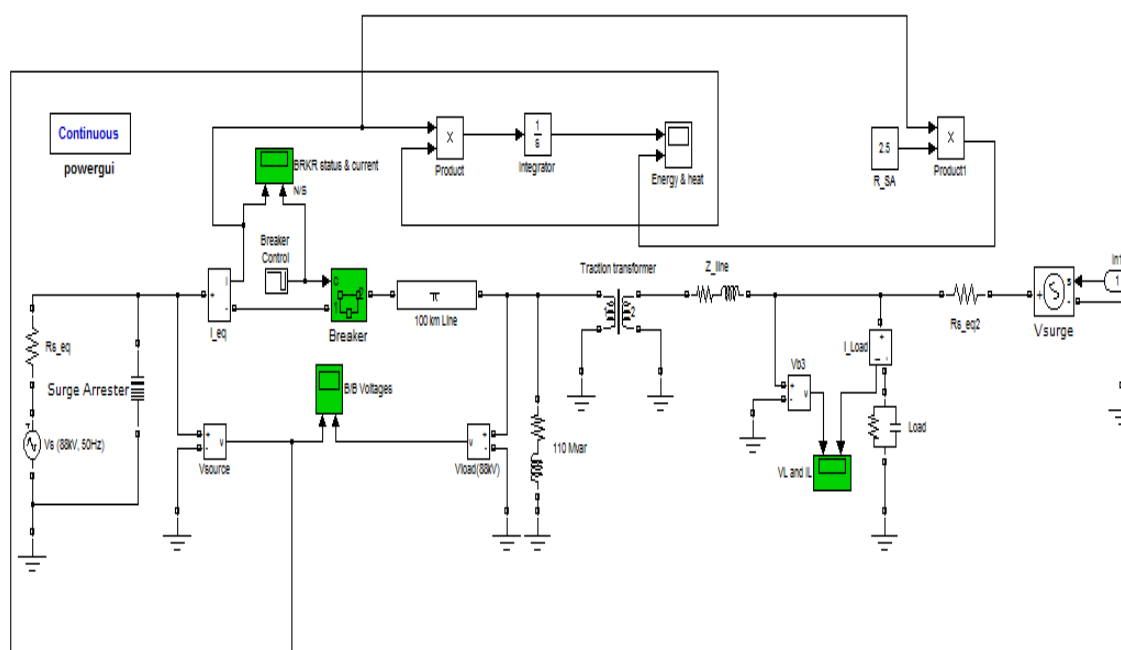


Figure A. 1 A simple circuit for simulating surges in PSB tool [79]

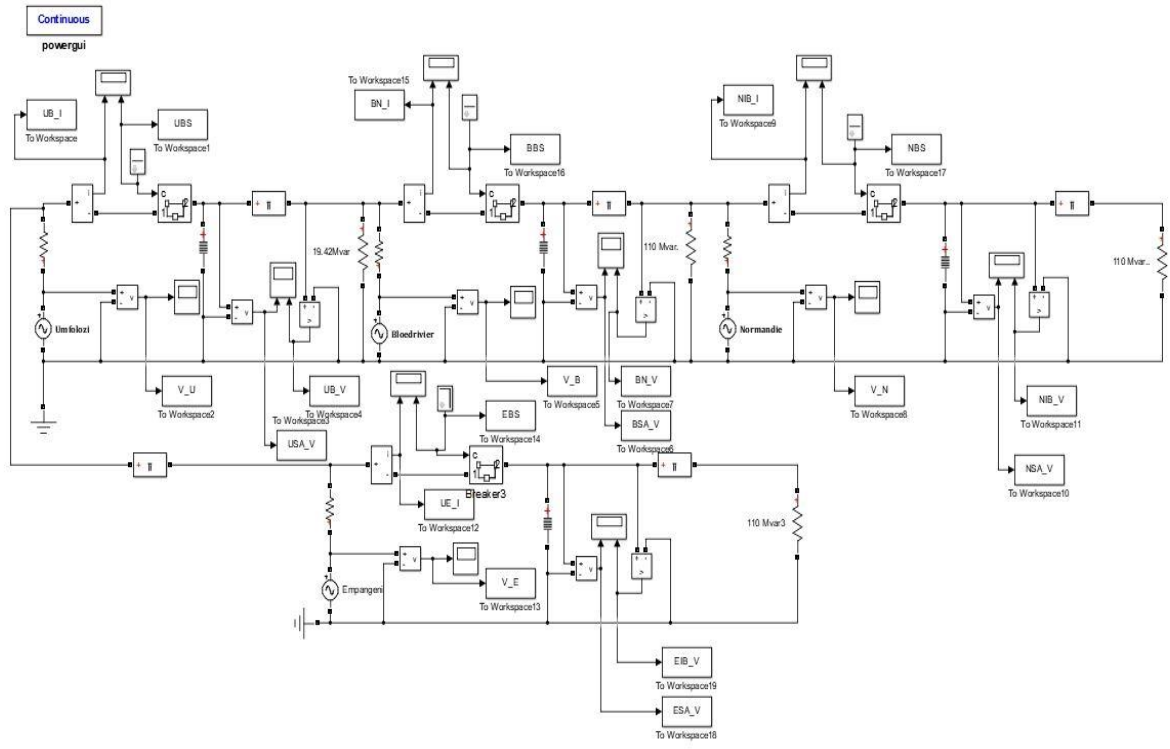


Figure A. 2 EGTN model in PSB tool

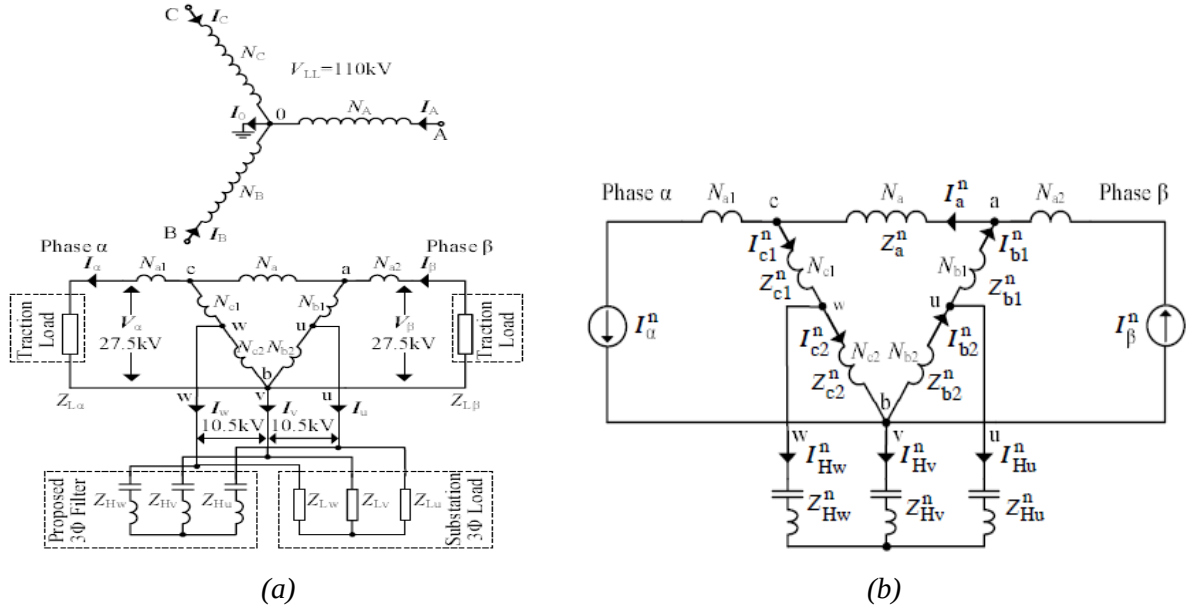


Figure A. 3 (a) Circuit diagram of the MPB transformer and (b) the harmonic equivalent circuit of the MPB transformer [81]

Table A. 4. Model parameters of the EGTN model in PSB tool

		PQ load (MW)			Line data (km)		Voltage source (kV)		Wolf conductor	
Bus #	1pf	0.85pf	0.7pf	Bus to bus	length	Bus #	AC RMS voltage at 50 Hz	Resistance (Ω) per km	Reactance (Ω) per km	
2	91.6, 0	77.9, 48.6	64.1, 65.0	1-2, 2-3	46.4	1	88 kV	0.1932	0.3065	
4	58.4, 0	49.6, 31.0	40.9, 41.5	3-4, 4-5	56.6	3				
6	24.0, 0	20.4, 12.7	18.8, 17.0	5-6	64.7	5				
7	22.8, 0	19.4, 12.1	16.0, 16.2	1-7	64.7	7				
Breaker data		Fault data					Breaker states indications			
Contact resistance (Ω)	10 ⁻⁶	Fault start time		1.00 seconds			Closed	“1” is for no fault condition		
Contact capacitance (F)	∞	Fault clearing time		1.04 seconds			Opened	“0” is a fault condition		
		Fault duration		0.04 seconds			Surge arrester characteristics V _{ref} : 88000 # COL: 3 k ₁ : 0.9950, k ₂ : 1.0, k ₃ : 0.0915, α ₁ :50, α ₂ : 25, α ₃ :16.5			
		Fault locations		1, 3, 5 and 7						

Table A. 5 Generator data utilized for EGTN modelling in PSAT tool

Umfolozi generator				Bloedrivier & Normandie generators			
Power (MW)	100			Power (MW)	100		
Voltage (kV)	400			Voltage (kV)	275		
d-axis reactance (pu)		q-axis reactance (pu)		d-axis reactance (pu)		q-axis reactance (pu)	
X_d	0.8958	X_q	0.8645	X_d	1.3125	X_q	1.2578
X'_d	0.1198	X'_q	0.1969	X'_d	0.1813	X'_q	0.2500
X''_d	0.0000	X''_q	0.0000	X''_d	0.0000	X''_q	0.0000
T'_{q0}	0.5350	T''_{q0}	0	T'_{q0}	0.6000	T''_{q0}	0.0000

Table A. 3 Voltage controlled, swing and transformers buses data for EGTN simulations in PSAT tool

PV buses 1, 3, 5 and 7		Swing bus 6	Transformers			
Active Power (pu)	1.630	Voltage (pu)	Bus	HV and MV ratio	Resistance (pu)	Reactance (pu)
Voltage (pu)	1.025	Reference phase angle (rad)	1	400/88	0.000	0.0625
Q _{max}	99.000		3	275/88		0.0586
Q _{min}	-99.000		5	400/88		0.0625
V _{max}	1.100					
V _{min}	0.900					

Table A. 4 EGTN line and fault parameters in PSAT tool

Line data						Fault data	
Line sections	Length (km)	Wolf conductor parameters				Fault parameters	
		R/km	X/km	R pu	X pu	Fault start time (s)	1.000
1 - 2	46.4	0.1932	0.3065	0.0668	0.1060	Fault end time (s)	1.040
1 - 7	64.7			0.0932	0.1478	Fault resistance (pu)	0.000
2 - 3	46.4			0.0668	0.1060	Fault reactance (pu)	0.001
3 - 4	56.6			0.0815	0.1293		
4 - 5	56.6			0.0815	0.1293		
6 - 7	64.7			0.0932	0.1478		

Table A. 5 Load data for EGTN simulations in PSAT tool

Load data									
Bus #	Statistical PQ loads		S pu	1pf		0.85pf		0.7pf	
				P pu	Q pu	P pu	Q pu	P pu	Q pu
2	0.63	0.00	0.63	0.63	0	0.54	0.33	0.44	0.45
4	0.92	0.00	0.92	0.92	0	0.78	0.49	0.64	0.65
7	0.23	0.05	0.23	0.23	0	0.20	0.12	0.16	0.16
8	0.58	0.00	0.58	0.58	0	0.50	0.31	0.41	0.41
9	0.25	0.03	0.25	0.25	0	0.21	0.13	0.18	0.18
10	0.24	0.00	0.24	0.24	0	0.20	0.13	0.17	0.17
11	0.22	0.04	0.23	0.23	0	0.19	0.12	0.16	0.16

Table A. 6 voltage source, breaker and surge arrester data for EGTN simulations in ATP tool

AC Voltage sources at buses 1, 3, 5 & 7		Surge arrester parameters			
		Attributes		V-I characteristic	
Amplitude (V)	88000	V _{ref}	88000	I (A)	U(V)
Frequency (Hz)	50	V _{flash}	-1	0.003	33000
Angle (deg)	0	V ₀	0	0.01	35000
T-start (sec)	-1	# COL	3	0.5	42500
T-stop (sec)	100	#SER	1	5	48000
Breakers at buses 1, 3, 5 & 7		ErrLim	0.05	50	55000
T-cl_1 (s)	0.01			500	62000
T-op_1 (s)	-1			2500	68000
T-cl_2(s)	0.01			5000	72100
T-op_2 (s)	-1			10000	77300
T-cl_3(s)	0.01				
T-op_3 (s)	-1				

Table A. 7 Data used in the computation of reliability indices of the EGTN

Umfolozi Feeder 1						Backbone section lengths	
Section Nr	Length	Load Point	MVA	Name	Nr of customers	2	12.9
1	27.79	LP1	15	Cwaka	1	4	19.72
3	6.53	LP2	10	Emekweni	1	6	13.31
5	5	LP3	3.5	Kombe	1	8	18.31
7	15	LP4	1	Intshamazi	1	10	8.96
9	5		1	Mpanda	1	12	18.2
11	0.01	LP6	1	Ulundi	1	14	11.27
13	0.13	LP7	1	Eqwasha	1	16	21.86
						18	15.57
Umfolozi Feeder 2						20	23.31
15	3.06	LP11	9	Skume	1	22	0.43
17	1.19	LP10	3.5	Engocweni	1	24	8.4
19	4.41	LP9	3	Mapaseni	1	26	15.4
21	9.93	LP8	4	Dubula	1	28	27.96
Bloedrivier Feeder 1						30	37.31
						Parameters	
23	4	LP15	5.5	Hlungwane	1	λ is 0.065 for equipment and 0.015 for transformers	
25	2.4	LP14	5.5	Dumba	1		
27	5	LP13	3	Mqwabe	1	r is 1 hr for equipment on lateral and 5 hours for equipment on the backbone	
29	3	LP12	1	Sikame	1		

Appendix B

Table B. 1 Reliability evaluation of Umfolozi 88 kV feeder 1 in the EGTN

Umfolozi 88kV feeder 1 reliability indices			Difference (%) between FEAM and SMt
Reliability index	Evaluation methods		
	FMEA	SMt	
SAIFI	7.1194	7.6420	7.3405
SAIDI	22.6182	22.1450	-2.0921
CAIDI	3.1770	3.4360	8.1523
ASAI	0.9974	0.9975	0.0072
ASUI	0.0026	0.0025	-3.8462
ENS (kWh)	1022776.2000	1022665.2470	-0.0109
AENS (kWh)	68185.0800	68177.6831	-0.0109

Table B. 2 Reliability evaluation of Umfolozi 88 kV feeder 2 in the EGTN

Umfolozi 88kV feeder 2 reliability indices			Difference(%) between FEAM and SM
Reliability index	Evaluation methods		
	FMEA	SMt	
SAIFI	4.2215	4.2120	-0.22504
SAIDI	16.1186	16.4150	1.83887
CAIDI	3.8182	3.5600	-6.76235
ASAI	0.9995	0.9981	-0.13745
ASUI	0.0005	0.0019	-0.13745
ENS (kWh)	318257.9000	318044.0000	-0.06721
AENS (kWh)	21217.1933	21202.9333	-0.06721

Table B. 3 Reliability evaluation of Bloedrivier 88 kV feeder 1 in the EGTN

Bloedrivier 88kV feeder 1 reliability indices			Difference(%) between FEAM and SM
Reliability index	Evaluation methods		
	FMEA	SM	
SAIFI	4.8426	4.5050	-6.9715
SAIDI	26.9428	26.9990	0.2086
CAIDI	0.1797	0.1750	-2.6155
ASAI	0.9994	0.9969	-0.2484
ASUI	0.0006	0.0031	-0.2484
ENS (kWh)	401053.8000	401053.2930	-0.0001
AENS (kWh)	26736.9200	26736.8862	-0.0001

Table B. 4 Post fault voltage magnitudes in the EGTN for a transient fault at bus #1 in PSB tool

Bus #	Transient state voltages	Steady state voltages	Difference %
1	88.0000	88.0000	0.0000
2	84.9340	84.9320	0.0024
3	88.0000	88.0000	0.0000
4	84.9560	84.9550	0.0012
5	88.0000	88.0000	0.0000
6	88.0000	88.0000	0.0000
7	85.9890	85.9890	0.0000

Table B. 5 Post fault voltage magnitudes in the EGTN for a transient fault at bus # 3 in PSB tool

Bus #	Transient state voltages	Steady state voltages	Difference %
1	87.9960	88.0000	-0.0045
2	84.9330	84.9320	0.0012
3	87.9960	88.0000	-0.0045
4	87.9960	84.9550	3.5795
5	87.9960	88.0000	-0.0045
6	87.9960	88.0000	-0.0045
7	85.9860	85.9890	-0.0035

Table B. 6 Post fault voltage magnitudes in the EGTN for a transient fault at bus # 5 in PSB tool

Bus #	Transient state voltages	Steady state voltages	Difference %
1	87.9990	88.0000	-0.0011
2	84.9320	84.9320	0.0000
3	87.9990	88.0000	-0.0011
4	84.9550	84.9550	0.0000
5	87.9990	88.0000	-0.0011
6	87.9990	88.0000	-0.0011
7	85.9890	85.9890	0.0000

Table B. 7 Post fault voltage magnitudes in the EGTN for a transient fault at bus # 7 in PSB tool

Bus #	Transient state voltages	Steady state voltages	Difference %
1	88.0000	88.0000	0.0000
2	84.9320	84.9320	0.0000
3	88.0000	88.0000	0.0000
4	84.9550	84.9550	0.0000
5	88.0000	88.0000	0.0000
6	88.0000	88.0000	0.0000
7	85.9890	85.9890	0.0000

Table B. 8 Post fault voltage magnitudes in the EGTN for a transient fault at bus # 1 in PSB tool (0.85pf)

Bus #	Transient state voltages	Steady state voltages	Difference %
1	88.0000	88.0000	0.0000
2	85.0690	84.9320	0.1613
3	88.0000	88.0000	0.0000
4	85.1400	84.9550	0.2178
5	88.0000	88.0000	0.0000
6	88.0000	88.0000	0.0000
7	86.0470	85.9890	0.0675

Table B. 9 Post fault voltage magnitudes in the EGTN for a transient fault at bus # 3 in PSB tool (0.85pf)

Bus #	Transient state voltages	Steady state voltages	Difference %
1	88.9970	88.0000	1.1330
2	85.0680	84.9320	0.1601
3	87.9970	88.0000	-0.0034
4	85.1430	84.9550	0.2213
5	87.9970	88.0000	-0.0034
6	87.9970	88.0000	-0.0034
7	86.0460	85.9890	0.0663

Table B. 10 Post fault voltage magnitudes in the EGTN for a transient fault at bus # 5 in PSB tool (0.85pf)

Bus #	Transient state voltages	Steady state voltages	Difference %
1	87.9980	88.0000	-0.0023
2	85.0710	84.9320	0.1637
3	87.9980	88.0000	-0.0023
4	85.1410	84.9550	0.2189
5	87.9980	88.0000	-0.0023
6	87.9980	88.0000	-0.0023
7	86.0460	85.9890	0.0663

Table B. 11 Post fault voltage magnitudes in the EGTN for a transient fault at bus #7 in PSB tool (0.85pf)

Bus #	Transient state voltages	Steady state voltages	Difference %
1	88.9990	88.0000	1.1352
2	85.0660	84.9320	0.1578
3	87.9990	88.0000	-0.0011
4	85.1400	84.9550	0.2178
5	87.9990	88.0000	-0.0011
6	87.9990	88.0000	-0.0011
7	86.0470	85.9890	0.0675

Table B. 12 Post fault voltage magnitudes in the EGTN for a transient fault at bus #1 in PSB tool (0.7pf)

Bus #	Transient state voltages	Steady state voltages	Difference %
1	87.9980	88.0000	-0.0023
2	85.2140	84.9320	0.3320
3	87.9980	88.0000	-0.0023
4	85.3760	84.9550	0.4956
5	87.9980	88.0000	-0.0023
6	87.9980	88.0000	-0.0023
7	86.0840	85.9890	0.1105

Table B. 13 Post fault voltage magnitudes in the EGTN for a transient fault at bus #3 in PSB tool (0.7pf)

Bus #	Transient state voltages	Steady state voltages	Difference %
1	88.0000	88.0000	0.0000
2	85.2140	84.9320	0.3320
3	87.9960	88.0000	-0.0045
4	85.3730	84.9550	0.4920
5	87.9960	88.0000	-0.0045
6	87.9960	88.0000	-0.0045
7	86.0810	85.9890	0.1070

Table B. 14 Post fault voltage magnitudes in the EGTN for a transient fault at bus #5 in PSB tool (0.7pf)

Bus #	Transient state voltages	Steady state voltages	Difference %
1	88.0000	88.0000	0.0000
2	85.2130	84.9320	0.3309
3	88.0000	88.0000	0.0000
4	85.3770	84.9550	0.4967
5	88.0000	88.0000	0.0000
6	88.0000	88.0000	0.0000
7	86.0840	85.9890	0.1105

Table B. 15 Post fault voltage magnitudes in the EGTN for a transient fault at bus #7 in PSB tool (0.7pf)

Bus #	Transient state voltages	Steady state voltages	Difference %
1	87.9980	88.0000	-0.0023
2	85.2180	84.9320	0.3367
3	87.9980	88.0000	-0.0023
4	85.3760	84.9550	0.4956
5	87.9980	88.0000	-0.0023
6	87.9980	88.0000	-0.0023
7	86.0840	85.9890	0.1105

Table B. 16 88 kV surge arrester technical parameters specified by Eskom

Parameter		Units	Eskom spec
Maximum continuous overvoltage, $MCOV$		kV	56
Rated voltage, U_r		kV	70
Residual voltage, U_{res}		kV	210
discharge current, I_d		A	*
Nominal discharge current, I_n		kA	10
Energy absorption capability, EAC		kJ/kV _{MCOV}	3.4
Classification			2
*	Not required		
**	Not specified		
***	by FAT		

Table B. 17 Umfolozi surge arrester parameters for a fault at Umfolozi under full loading conditions

Parameter	Units	PSB	ABB		Siemens			Areva	
Maximum continuous overvoltage, $MCOV$	kV	49.6500	72		58			58	
Rated voltage, U_r	kV	62.0625	90		72			72	
Residual voltage, U_{res}	kV	*	***	***	184,184	206,206	169,173	196	215
discharge current, I_d	A	0.8667	***	***	***			***	***
Nominal discharge current, I_n	kA	*	10	20	10	20	10	10	20
Energy absorption capability, EAC	kJ/kV	1.8	3.0,5.2,5.5,9.0	13.3,21.0	5,6	5,8	8,10	**	**
Classification		*****	1,2,3,	4,5	2,3	2,3	3,4	2	2
*	Incomputable								
**	Not specified								
***	Confirmed by FAT								

Table B. 18 Bloedrivier surge arrester parameters for a fault at Umfolozi under full loading conditions

Parameter	Units	PSB	ABB		Siemens			Areva	
Maximum continuous overvoltage, $MCOV$	kV	49.0400	72		58			58	
Rated voltage, U_r	kV	61.3000	90		72			72	
Residual voltage, U_{res}	kV	*	***	***	184,184	206,206	169,173	196	215
discharge current, I_d	A	0.1365	***	***	***			***	***
Nominal discharge current, I_n	kA	*	10	20	10	20	10	10	20
Energy absorption capability, EAC	kJ/kV _{MCOV}	0.1	3.0,5.2,5.5,9.0	13.3,21.0	5,6	5,8	8,10	**	**
Classification		*****	1,2,3,	4,5	2,3	2,3	3,4	2	2
*	Not required								
**	Not specified								
***	by FAT								

Table B. 19 Normandie surge arrester parameters for a fault at Umfolozi under full loading conditions

Parameter		Units	PSB	ABB		Siemens			Areva	
Maximum continuous overvoltage, $MCOV$		kV	49.0500	72		58			58	
Rated voltage, U_r		kV	61.3125	90		72			72	
Residual voltage, U_{res}		kV	*	***	***	184,184	206,206	169,173	196	215
discharge current, I_d		A	2.3711	***	***	***			***	***
Nominal discharge current, I_n		kA	*	10	20	10	20	10	10	20
Energy absorption capability, EAC		kJ/kV $_{MCOV}$	12.3	3.0,5.2,5.5,9.0	13.3,21.0	5,6	5,8	8,10	**	**
Classification			*****	1,2,3,	4,5	2,3	2,3	3,4	2	2
*	Incomputable	**	Not specified	***	Confirmed by FAT					

Table B. 20 Empangeni surge arrester parameters for a fault at Umfolozi under full loading conditions

Parameter		Units	PSB	ABB		Siemens			Areva	
Maximum continuous overvoltage, $MCOV$		kV	49.650	72		58			58	
Rated voltage, U_r		kV	62.063	90		72			72	
Residual voltage, U_{res}		kV	*	***	***	184,184	206,206	169,173	196	215
discharge current, I_d		A	0.8197	***	***	***			***	***
Nominal discharge current, I_n		kA	*	10	20	10	20	10	10	20
Energy absorption capability, EAC		kJ/kV	1.6	3.0,5.2,5.5,9.0	13.3,21.0	5,6	5,8	8,10	**	**
Classification			*****	1,2,3,	4,5	2,3	2,3	3,4	2	2
*	Not required									
**	Not specified									
***	by FAT									

Table B. 21 Umfolozi surge arrester parameters for a fault at Bloedrivier under full loading conditions

Parameter		Units	PSB	ABB		Siemens			Areva	
Maximum continuous overvoltage, $MCOV$		kV	49.6400	72		58			58	
Rated voltage, U_r		kV	62.0500	90		72			72	
Residual voltage, U_{res}		kV	*	***	***	184,184	206,206	169,173	196	215
discharge current, I_d		A	0.8635	***	***	***			***	***
Nominal discharge current, I_n		kA	*	10	20	10	20	10	10	20
Energy absorption capability, EAC		kJ/kV	0	3.0,5.2,5.5,9.0	13.3,21.0	5,6	5,8	8,10	**	**
Classification			*****	1,2,3,	4,5	2,3	2,3	3,4	2	2
*	Not required									
**	Not specified									
***	by FAT									

Table B. 22 Bloedrivier surge arrester parameters for a fault at Bloedrivier under full loading conditions

Parameter		Units	PSB	ABB		Siemens			Areva	
Maximum continuous overvoltage, $MCOV$		kV	49.0400	72		58			58	
Rated voltage, U_r		kV	61.3000	90		72			72	
Residual voltage, U_{res}		kV	*	***	***	184,184	206,206	169,173	196	215
discharge current, I_d		A	0.6871	***	***	***			***	***
Nominal discharge current, I_n		kA	*	10	20	10	20	10	10	20
Energy absorption capability, EAC		kJ/kV	0	3.0,5.2,5.5,9.0	13.3,21.0	5,6	5,8	8,10	**	**
Classification			*****	1,2,3,	4,5	2,3	2,3	3,4	2	2
*	Not required									
**	Not specified									
***	by FAT									

Table B. 23 Normandie surge arrester parameters for a fault at Bloedrivier under full loading conditions

Parameter		Units	PSB	ABB		Siemens			Areva	
Maximum continuous overvoltage, $MCOV$		kV	49.0500	72		58			58	
Rated voltage, U_r		kV	61.313	90		72			72	
Residual voltage, U_{res}		kV	*	***	***	184,184	206,206	169,173	196	215
discharge current, I_d		A	2.3177	***	***	***			***	***
Nominal discharge current, I_n		kA	*	10	20	10	20	10	10	20
Energy absorption capability, EAC		kJ/kV	0	3.0,5.2,5.5,9.0	13.3,21.0	5,6	5,8	8,10	**	**
Classification			*****	1,2,3,	4,5	2,3	2,3	3,4	2	2
*	Not required									
**	Not specified									
***	by FAT									

Table B. 24 Empangeni surge arrester parameters for a fault at Bloedrivier under full loading conditions

Parameter		Units	PSB	ABB		Siemens			Areva	
Maximum continuous overvoltage, $MCOV$		kV	49.640	72		58			58	
Rated voltage, U_r		kV	62.050	90		72			72	
Residual voltage, U_{res}		kV	*	***	***	184,184	206,206	169,173	196	215
discharge current, I_d		A	0.8667	***	***	***			***	***
Nominal discharge current, I_n		kA	*	10	20	10	20	10	10	20
Energy absorption capability, EAC		kJ/kV	0	3.0,5.2,5.5,9.0	13.3,21.0	5,6	5,8	8,10	**	**
Classification			*****	1,2,3,	4,5	2,3	2,3	3,4	2	2
*	Not required									
**	Not specified									
***	by FAT									

Table B. 25 Umfolozi surge arrester parameters for a fault at Normandie under full loading conditions

Parameter		Units	PSB	ABB		Siemens			Areva	
Maximum continuous overvoltage, $MCOV$		kV	49.6500	72		58			58	
Rated voltage, U_r		kV	62.0625	90		72			72	
Residual voltage, U_{res}		kV	*	***	***	184,184	206,206	169,173	196	215
discharge current, I_d		A	0.4970	***	***	***			***	***
Nominal discharge current, I_n		kA	*	10	20	10	20	10	10	20
Energy absorption capability, EAC		kJ/kV	2.1	3.0,5.2,5.5,9.0	13.3,21.0	5,6	5,8	8,10	**	**
Classification			*****	1,2,3,	4,5	2,3	2,3	3,4	2	2
*	Not required									
**	Not specified									
***	by FAT									

Table B. 26 Bloedrivier surge arrester parameters for a fault at Normandie under full loading conditions

Parameter		Units	PSB	ABB		Siemens			Areva	
Maximum continuous overvoltage, $MCOV$		kV	49.040	72		58			58	
Rated voltage, U_r		kV	61.300	90		72			72	
Residual voltage, U_{res}		kV	*	***	***	184,184	206,206	169,173	196	215
discharge current, I_d		A	0.3950	***	***	***			***	***
Nominal discharge current, I_n		kA	*	10	20	10	20	10	10	20
Energy absorption capability, EAC		kJ/kV	0.4	3.0,5.2,5.5,9.0	13.3,21.0	5,6	5,8	8,10	**	**
Classification			*****	1,2,3,	4,5	2,3	2,3	3,4	2	2
*	Not required									
**	Not specified									
***	by FAT									

Table B. 27 Normandie surge arrester parameters for a fault at Normandie under full loading conditions

Parameter	Units	PSB	ABB		Siemens			Areva	
Maximum continuous overvoltage, $MCOV$	kV	49.0488	72		58			58	
Rated voltage, U_r	kV	61.3110	90		72			72	
Residual voltage, U_{res}	kV	*	***	***	184,184	206,206	169,173	196	215
discharge current, I_d	A	2.3620	***	***	***			***	***
Nominal discharge current, I_n	kA	*	10	20	10	20	10	10	20
Energy absorption capability, EAC	kJ/kV	3.6882	3.0,5.2,5.5,9.0	13.3,21.0	5,6	5,8	8,10	**	**
Classification			1,2,3,	4,5	2,3	2,3	3,4	2	2
*	Not required								
**	Not specified								
***	by FAT								

Table B. 28 Umfolozi surge arrester parameters for a fault at Normandie under full loading conditions

Parameter	Units	PSB	ABB		Siemens			Areva	
Maximum continuous overvoltage, $MCOV$	kV	49.650	72		58			58	
Rated voltage, U_r	kV	62.063	90		72			72	
Residual voltage, U_{res}	kV	*	***	***	184,184	206,206	169,173	196	215
discharge current, I_d	A	0.4700	***	***	***			***	***
Nominal discharge current, I_n	kA	*	10	20	10	20	10	10	20
Energy absorption capability, EAC	kJ/kV	1.9	3.0,5.2,5.5,9.0	13.3,21.0	5,6	5,8	8,10	**	**
Classification		*****	1,2,3,	4,5	2,3	2,3	3,4	2	2
*	Not required								
**	Not specified								

Table B. 29 Umfolozi surge arrester parameters for a fault at Empangeni under full loading conditions

Parameter	Units	PSB	ABB		Siemens			Areva	
Maximum continuous overvoltage, $MCOV$	kV	49.6500	72		58			58	
Rated voltage, U_r	kV	62.0625	90		72			72	
Residual voltage, U_{res}	kV	*	***	***	184,184	206,206	169,173	196	215
discharge current, I_d	A	0.8654	***	***	***			***	***
Nominal discharge current, I_n	kA	*	10	20	10	20	10	10	20
Energy absorption capability, EAC	kJ/kV	0.2	3.0,5.2,5.5,9.0	13.3,21.0	5,6	5,8	8,10	**	**
Classification		*****	1,2,3,	4,5	2,3	2,3	3,4	2	2
* Not required									
** Not specified									
*** by FAT									

Table B. 30 Bloedrivier surge arrester parameters for a fault at Empangeni under full loading conditions

Parameter	Units	PSB	ABB		Siemens			Areva	
Maximum continuous overvoltage, $MCOV$	kV	49.0400	72		58			58	
Rated voltage, U_r	kV	61.3000	90		72			72	
Residual voltage, U_{res}	kV	*	***	***	184,184	206,206	169,173	196	215
discharge current, I_d	A	0.1365	***	***	***			***	***
Nominal discharge current, I_n	kA	*	10	20	10	20	10	10	20
Energy absorption capability, EAC	kJ/kV	0.1000	3.0,5.2,5.5,9.0	13.3,21.0	5,6	5,8	8,10	**	**
Classification		*****	1,2,3,	4,5	2,3	2,3	3,4	2	2
* Not required									
** Not specified									
*** by FAT									

Table B. 31 Normandie surge arrester parameters for a fault at Empangeni under full loading conditions

Parameter	Units	PSB	ABB		Siemens			Areva	
Maximum continuous overvoltage, $MCOV$	kV	49.050	72		58			58	
Rated voltage, U_r	kV	61.313	90		72			72	
Residual voltage, U_{res}	kV	*	***	***	184,184	206,206	169,173	196	215
discharge current, I_d	A	1.9015	***	***	***			***	***
Nominal discharge current, I_n	kA	*	10	20	10	20	10	10	20
Energy absorption capability, EAC	kJ/kV	1.9	3.0,5.2,5.5,9.0	13.3,21.0	5,6	5,8	8,10	**	**
Classification		*****	1,2,3,	4,5	2,3	2,3	3,4	2	2
*	Not required								
**	Not specified								
***	by FAT								

Table B. 32 Empangeni surge arrester parameters for a fault at Empangeni under full loading conditions

Parameter	Units	PSB	ABB		Siemens			Areva	
Maximum continuous overvoltage, $MCOV$	kV	49.6500	72		58			58	
Rated voltage, U_r	kV	62.0625	90		72			72	
Residual voltage, U_{res}	kV	*	***	***	184,184	206,206	169,173	196	215
discharge current, I_d	A	8.5989	***	***	***			***	***
Nominal discharge current, I_n	kA	*	10	20	10	20	10	10	20
Energy absorption capability, EAC	kJ/kV	8.6	3.0,5.2,5.5,9.0	13.3,21.0	5,6	5,8	8,10	**	**
Classification		*****	1,2,3,	4,5	2,3	2,3	3,4	2	2
*	Not required								
**	Not specified								
***	by FAT								

Table B. 33 Umfolozi surge arrester parameters for a fault at Umfolozi under 0.85pf loading conditions

Parameter	Units	PSB	ABB		Siemens			Areva	
Maximum continuous overvoltage, $MCOV$	kV	49.67 93	72		58			58	
Rated voltage, U_r	kV	62.09 91	90		72			72	
Residual voltage, U_{res}	kV	*	***	***	184, 184	206,20 6	169,17 3	196	215
discharge current, I_d	A	0	***	***	***			***	***
Nominal discharge current, I_n	kA	*	10	20	10	20	10	10	20
Energy absorption capability, EAC	kJ/kV	0	3.0,5.2,5.5,9.0	13.3,21.0	5,6	5,8	8,10	**	**

Table B. 34 Bloedrivier surge arrester parameters for a fault at Umfolozi under 0.85pf loading conditions

Parameter	Units	PSB	ABB		Siemens			Areva	
Maximum continuous overvoltage, $MCOV$	kV	49.1146	72		58			58	
Rated voltage, U_r	kV	61.3933	90		72			72	
Residual voltage, U_{res}	kV	*	***	***	184,184	206,206	169,173	196	215
discharge current, I_d	A	0	***	***	***			***	***
Nominal discharge current, I_n	kA	*	10	20	10	20	10	10	20
Energy absorption capability, EAC	kJ/kV	0	3.0,5.2,5.5,9.0	13.3,21.0	5,6	5,8	8,10	**	**
Classification		*****	1,2,3,	4,5	2,3	2,3	3,4	2	2
* Not required									
** Not specified									
*** by FAT									

Table B. 35 Normandie surge arrester parameters for a fault at Umfolozi under 0.85pf loading conditions

Parameter	Units	PSB	ABB		Siemens			Areva	
Maximum continuous operating voltage, $MCOV$	kV	49.1556	72		58			58	
Rated voltage, U_r	kV	61.4445	90		72			72	
Residual voltage, U_{res}	kV	*	***	***	184,184	206,206	169,173	196	215
discharge current, I_d	A	0	***	***	***			***	***
Nominal discharge current, I_n	kA	*	10	20	10	20	10	10	20
Energy absorption capability, EAC	kJ/kV	0	3.0,5.2,5.5,9.0	13.3,21.0	5,6	5,8	8,10	**	**
Classification		*****	1,2,3,	4,5	2,3	2,3	3,4	2	2
* Not required									

**	Not specified									
***	Confirmed by FAT									

Table B. 36 Empangeni surge arrester parameters for a fault at Umfolozi under 0.85pf loading conditions

Parameter	Units	PSB	ABB		Siemens			Areva	
Maximum continuous overvoltage, $MCOV$	kV	49.6793	72		58			58	
Rated voltage, U_r	kV	62.09913	90		72			72	
Residual voltage, U_{res}	kV	*	***	***	184,184	206,206	169,173	196	215
discharge current, I_d	A	0.8197	***	***	***			***	***
Nominal discharge current, I_n	kA	*	10	20	10	20	10	10	20
Energy absorption capability, EAC	kJ/kV	0	3.0,5.2,5.5,9.0	13.3,21.0	5,6	5,8	8,10	**	**
Classification		*****	1,2,3,	4,5	2,3	2,3	3,4	2	2
* Not required									
** Not specified									
*** by FAT									

Table B. 37 Umfolozi surge arrester parameters for a fault at Bloedrivier under 0.85pf loading conditions

Parameter	Units	PSB	ABB		Siemens			Areva	
Maximum continuous overvoltage, $MCOV$	kV	49.6787	72		58			58	
Rated voltage, U_r	kV	62.0984	90		72			72	
Residual voltage, U_{res}	kV	*	***	***	184,184	206,206	169,173	196	215
discharge current, I_d	A	0	***	***	***			***	***
Nominal discharge current, I_n	kA	*	10	20	10	20	10	10	20
Energy absorption capability, EAC	kJ/kV	0	3.0,5.2,5.5,9.0	13.3,21.0	5,6	5,8	8,10	**	**
Classification		*****	1,2,3,	4,5	2,3	2,3	3,4	2	2
* Not required									
** Not specified									
*** by FAT									

Table B. 38 Bloedrivier surge arrester parameters for a fault at Bloedrivier under 0.85pf loading conditions

Maximum continuous overvoltage, $MCOV$	kV	49.1140	72		58			58	
Rated voltage, U_r	kV	61.3925	90		72			72	
Residual voltage, U_{res}	kV	*	***	***	184,184	206,206	169,173	196	215
discharge current, I_d	A	0	***	***	***			***	***
Nominal discharge current, I_n	kA	*	10	20	10	20	10	10	20
Energy absorption capability, EAC	kJ/kV	0	3.0,5.2,5.5,9.0	13.3,21.0	5,6	5,8	8,10	**	**
Classification		*****	1,2,3,	4,5	2,3	2,3	3,4	2	2
*	Not required								
**	Not specified								
***	by FAT								

Table B. 39 Normandie surge arrester parameters for a fault at Bloedrivier under 0.85pf loading conditions

Parameter	Units	PSB	ABB		Siemens			Areva	
Maximum continuous operating voltage, $MCOV$	kV	49.1573	72		58			58	
Rated voltage, U_r	kV	61.4466	90		72			72	
Residual voltage, U_{res}	kV	*	***	***	184,184	206,206	169,173	196	215
discharge current, I_d	A	0	***	***	***			***	***
Nominal discharge current, I_n	kA	*	10	20	10	20	10	10	20
Energy absorption capability, EAC	kJ/kV	0	3.0,5.2,5.5,9.0	13.3,21.0	5,6	5,8	8,10	**	**
Classification		*****	1,2,3,	4,5	2,3	2,3	3,4	2	2
*	Not required								
**	Not specified								
***	by FAT								

Table B. 40 Empangeni surge arrester parameters for a fault at Bloedrivier under 0.85pf loading conditions

Parameter	Units	PSB	ABB		Siemens			Areva	
Maximum continuous operating voltage, <i>MCOV</i>	kV	49.6793	72		58			58	
Rated voltage, <i>U_r</i>	kV	62.0991	90		72			72	
Residual voltage, <i>U_{res}</i>	kV	*	***	***	184,184	206,206	169,173	196	215
discharge current, <i>I_d</i>	A	0	***	***	***			***	***
Nominal discharge current, <i>I_n</i>	kA	*	10	20	10	20	10	10	20
Energy absorption capability, <i>EAC</i>	kJ/kV	0	3.0,5.2,5.5,9.0	13.3,21.0	5,6	5,8	8,10	**	**
Classification		*****	1,2,3,	4,5	2,3	2,3	3,4	2	2
* Not required									
** Not specified									
*** by FAT									

Table B. 41 Umfolozi surge arrester parameters for a fault at Normandie under 0.85pf conditions

Parameter	Units	PSB	ABB		Siemens			Areva	
Maximum continuous overvoltage, <i>MCOV</i>	kV	49.6787	72		58			58	
Rated voltage, <i>U_r</i>	kV	62.0984	90		72			72	
Residual voltage, <i>U_{res}</i>	kV	*	***	***	184,184	206,206	169,173	196	215
discharge current, <i>I_d</i>	A	24.0519	***	***	***			***	***
Nominal discharge current, <i>I_n</i>	kA	*	10	20	10	20	10	10	20
Energy absorption capability, <i>EAC</i>	kJ/kV	98205	3.0,5.2,5.5,9.0	13.3,21.0	5,6	5,8	8,10	**	**
Classification		*****	1,2,3,	4,5	2,3	2,3	3,4	2	2
* Not required									
** Not specified									
*** by FAT									

Table B. 42 Bloedrivier surge arrester parameters for a fault at Normandie under 0.85pf loading conditions

Parameter		Units	PSB	ABB		Siemens			Areva	
Maximum continuous overvoltage, $MCOV$		kV	49.1158	72		58			58	
Rated voltage, U_r		kV	61.3948	90		72			72	
Residual voltage, U_{res}		kV	*	***	***	184,184	206,206	169,173	196	215
discharge current, I_d		A	8.3107	***	***	***			***	***
Nominal discharge current, I_n		kA	*	10	20	10	20	10	10	20
Energy absorption capability, EAC		kJ/kV	32735	3.0,5.2,5.5,9.0	13.3,21.0	5,6	5,8	8,10	**	**
Classification			*****	1,2,3,	4,5	2,3	2,3	3,4	2	2
*	Not required									
**	Not specified									
***	by FAT									

Table B. 43 Normandie surge arrester parameters for a fault at Normandie under 0.85pf loading conditions

Parameter		Units	MSPB	ABB		Siemens			Areva	
Maximum continuous overvoltage, $MCOV$		kV	49.1562	72		58			58	
Rated voltage, U_r		kV	61.4453	90		72			72	
Residual voltage, U_{res}		kV	*	***	***	184,184	206,206	169,173	196	215
discharge current, I_d		A	8.5828	***	***	***			***	***
Nominal discharge current, I_n		kA	*	10	20	10	20	10	10	20
Energy absorption capability, EAC		kJ/kV	33768	3.0,5.2,5.5,9.0	13.3,21.0	5,6	5,8	8,10	**	**
Classification			*****	1,2,3,	4,5	2,3	2,3	3,4	2	2
*	Not required									
**	Not specified									
***	by FAT									

Table B. 44 Empangeni surge arrester parameters for a fault at Normandie under 0.85pf loading conditions

Parameter		Units	PSB	ABB		Siemens			Areva	
Maximum continuous overvoltage, $MCOV$		kV	49.6787	72		58			58	
Rated voltage, U_r		kV	62.0984	90		72			72	
Residual voltage, U_{res}		kV	*	***	***	184,184	206,206	169,173	196	215
discharge current, I_d		A	8.5828	***	***	***			***	***
Nominal discharge current, I_n		kA	*	10	20	10	20	10	10	20
Energy absorption capability, EAC		kJ/kV	34387	3.0,5.2,5.5,9.0	13.3,21.0	5,6	5,8	8,10	**	**
Classification			*****	1,2,3,	4,5	2,3	2,3	3,4	2	2
*	Not required									
**	Not specified									
***	by FAT									

Table B. 45 Umfolozi surge arrester parameters for a fault at Empangeni under 0.85pf loading conditions

Parameter		Units	PSB	ABB		Siemens			Areva	
Maximum continuous overvoltage, $MCOV$		kV	49.6793	72		58			58	
Rated voltage, U_r		kV	62.0991	90		72			72	
Residual voltage, U_{res}		kV	*	***	***	184,184	206,206	169,173	196	215
discharge current, I_d		A	0	***	***	***			***	***
Nominal discharge current, I_n		kA	*	10	20	10	20	10	10	20
Energy absorption capability, EAC		kJ/kV	0	3.0,5.2,5.5,9.0	13.3,21.0	5,6	5,8	8,10	**	**
Classification			*****	1,2,3,	4,5	2,3	2,3	3,4	2	2
*	Not required									
**	Not specified									
***	by FAT									

Table B. 46 Bloedrivier surge arrester parameters for a fault at Empangeni under 0.85pf loading conditions

Parameter	Units	PSB	ABB		Siemens			Areva	
Maximum continuous overvoltage, $MCOV$	kV	49.1129	72		58			58	
Rated voltage, U_r	kV	61.3911	90		72			72	
Residual voltage, U_{res}	kV	*	***	***	184,184	206,206	169,173	196	215
discharge current, I_d	A	0	***	***	***			***	***
Nominal discharge current, I_n	kA	*	10	20	10	20	10	10	20
Energy absorption capability, EAC	kJ/kV	0	3.0,5.2,5.5,9.0	13.3,21.0	5,6	5,8	8,10	**	**
Classification		*****	1,2,3,	4,5	2,3	2,3	3,4	2	2
*	Not required								
**	Not specified								
***	by FAT								

Table B. 47 Normandie surge arrester parameters for a fault at Empangeni under 0.85pf loading conditions

Parameter	Units	PSB	ABB		Siemens			Areva	
Maximum continuous overvoltage, $MCOV$	kV	49.1556	72		58			58	
Rated voltage, U_r	kV	61.4445	90		72			72	
Residual voltage, U_{res}	kV	*	***	***	184,184	206,206	169,173	196	215
discharge current, I_d	A	0	***	***	***			***	***
Nominal discharge current, I_n	kA	*	10	20	10	20	10	10	20
Energy absorption capability, EAC	kJ/kV	0	3.0,5.2,5.5,9.0	13.3,21.0	5,6	5,8	8,10	**	**
Classification		*****	1,2,3,	4,5	2,3	2,3	3,4	2	2
*	Not required								
**	Not specified								
***	by FAT								

Table B. 48 Empangeni surge arrester parameters for a fault at Empangeni under 0.85pf loading conditions

Parameter	Units	PSB	ABB		Siemens			Areva	
Maximum continuous overvoltage, $MCOV$	kV	49.6793	72		58			58	
Rated voltage, U_r	kV	62.0991	90		72			72	
Residual voltage, U_{res}	kV	*	***	***	184,184	206,206	169,173	196	215
discharge current, I_d	A	0	***	***	***			***	***
Nominal discharge current, I_n	kA	*	10	20	10	20	10	10	20
Energy absorption capability, EAC	kJ/kV	0	3.0,5.2,5.5,9.0	13.3,21.0	5,6	5,8	8,10	**	**

Classification		*****	1,2,3,	4,5	2,3	2,3	3,4	2	2
*	Not required								
**	Not specified								
***	by FAT								

Table B. 49 Umfolozi surge arrester parameters for a fault at Umfolozi under 0.7pf loading conditions

Parameter	Units	PSB	ABB		Siemens			Areva	
Maximum continuous overvoltage, $MCOV$	kV	49.7006	72		58			58	
Rated voltage, U_r	kV	62.1258	90		72			72	
Residual voltage, U_{res}	kV	*	***	***	184,184	206,206	169,173	196	215
discharge current, I_d	A	3.5276	***	***	***			***	***
Nominal discharge current, I_n	kA	*	10	20	10	20	10	10	20
Energy absorption capability, EAC	kJ/kV	14060	3.0,5.2,5.5,9.0	13.3,21.0	5,6	5,8	8,10	**	**
Classification		*****	1,2,3,	4,5	2,3	2,3	3,4	2	2
*	Not required								
**	Not specified								
***	by FAT								

Table B. 50 Bloedrivier surge arrester parameters for a fault at Umfolozi under 0.7pf loading conditions

Parameter	Units	PSB	ABB		Siemens			Areva	
Maximum continuous overvoltage, $MCOV$	kV	49.1983	72		58			58	
Rated voltage, U_r	kV	61.4979	90		72			72	
Residual voltage, U_{res}	kV	*	***	***	184,184	206,206	169,173	196	215
discharge current, I_d	A	0.7975	***	***	***			***	***
Nominal discharge current, I_n	kA	*	10	20	10	20	10	10	20
Energy absorption capability, EAC	kJ/kV	30140	3.0,5.2,5.5,9.0	13.3,21.0	5,6	5,8	8,10	**	**
Classification		*****	1,2,3,	4,5	2,3	2,3	3,4	2	2
*	Not required								
**	Not specified								

Table B. 51 Normandie surge arrester parameters for a fault at Umfolozi under 0.7pf loading conditions

Parameter	Units	PSB	ABB		Siemens			Areva	
Maximum continuous overvoltage, $MCOV$	kV	49.2919	72		58			58	
Rated voltage, U_r	kV	61.6149	90		72			72	
Residual voltage, U_{res}	kV	*	***	***	184,184	206,206	169,173	196	215
discharge current, I_d	A	1.1430	***	***	***			***	***
Nominal discharge current, I_n	kA	*	10	20	10	20	10	10	20
Energy absorption capability, EAC	kJ/kV	4450	3.0,5.2,5.5,9.0	13.3,21.0	5,6	5,8	8,10	**	**
Classification		*****	1,2,3,	4,5	2,3	2,3	3,4	2	2
*	Not required								
**	Not specified								
***	by FAT								

Table B. 52 Empangeni surge arrester parameters for a fault at Umfolozi under 0.7pf loading conditions

Parameter	Units	PSB	ABB		Siemens			Areva	
Maximum continuous overvoltage, $MCOV$	kV	49.701	72		58			58	
Rated voltage, U_r	kV	62.126	90		72			72	
Residual voltage, U_{res}	kV	*	***	***	184,184	206,206	169,173	196	215
discharge current, I_d	A	0.1368	***	***	***			***	***
Nominal discharge current, I_n	kA	*	10	20	10	20	10	10	20
Energy absorption capability, EAC	kJ/kV	570	3.0,5.2,5.5,9.0	13.3,21.0	5,6	5,8	8,10	**	**
Classification		*****	1,2,3,	4,5	2,3	2,3	3,4	2	2
*	Not required								
**	Not specified								
***	by FAT								

Table B. 53 Umfolozi surge arrester parameters for a fault at Bloedrivier under 0.7pf loading conditions

Parameter	Units	PSB	ABB		Siemens			Areva	
Maximum continuous overvoltage, $MCOV$	kV	49.6989	72		58			58	
Rated voltage, U_r	kV	62.1236	90		72			72	
Residual voltage, U_{res}	kV	*	***	***	184,184	206,206	169,173	196	215
discharge current, I_d	A	0	***	***	***			***	***
Nominal discharge current, I_n	kA	*	10	20	10	20	10	10	20
Energy absorption capability, EAC	kJ/kV	0	3.0,5.2,5.5,9.0	13.3,21.0	5,6	5,8	8,10	**	**
Classification		*****	1,2,3,	4,5	2,3	2,3	3,4	2	2

Table B. 54 Bloedrivier surge arrester parameters for a fault at Bloedrivier under 0.7pf loading conditions

Parameter	Units	PSB	ABB		Siemens			Areva	
Maximum continuous overvoltage, $MCOV$	kV	49.1983	72		58			58	
Rated voltage, U_r	kV	61.4979	90		72			72	
Residual voltage, U_{res}	kV	*	***	***	184,184	206,206	169,173	196	215
discharge current, I_d	A	0	***	***	***			***	***
Nominal discharge current, I_n	kA	*	10	20	10	20	10	10	20
Energy absorption capability, EAC	kJ/kV	0	3.0,5.2,5.5,9.0	13.3,21.0	5,6	5,8	8,10	**	**
Classification		*****	1,2,3,	4,5	2,3	2,3	3,4	2	2
*	Not required								
**	Not specified								
***	by FAT								

Table B. 55 Normandie surge arrester parameters for a fault at Bloedrivier under 0.7pf loading conditions

Parameter	Units	PSB	ABB		Siemens			Areva	
Maximum continuous overvoltage, $MCOV$	kV	49.2901	72		58			58	
Rated voltage, U_r	kV	61.6126	90		72			72	
Residual voltage, U_{res}	kV	*	***	***	184,184	206,206	169,173	196	215
discharge current, I_d	A	0	***	***	***			***	***
Nominal discharge current, I_n	kA	*	10	20	10	20	10	10	20
Energy absorption capability, EAC	kJ/kV	0	3.0,5.2,5.5,9.0	13.3,21.0	5,6	5,8	8,10	**	**
Classification		*****	1,2,3,	4,5	2,3	2,3	3,4	2	2
*	Not required								

**	Not specified									
***	by FAT									

Table B. 56 Empangeni surge arrester parameters for a fault at Bloedrivier under 0.7 pf loading conditions

Parameter		Units	PSB	ABB		Siemens			Areva	
Maximum continuous overvoltage, $MCOV$		kV	49.6989	72		58			58	
Rated voltage, U_r		kV	62.1236	90		72			72	
Residual voltage, U_{res}		kV	*	***	***	184,184	206,206	169,173	196	215
discharge current, I_d		A	0	***	***	***			***	***
Nominal discharge current, I_n		kA	*	10	20	10	20	10	10	20
Energy absorption capability, EAC		kJ/kV	0	3.0,5.2,5.5,9.0	13.3,21.0	5,6	5,8	8,10	**	**
Classification			*****	1,2,3,	4,5	2,3	2,3	3,4	2	2
*	Not required									
**	Not specified									
***	by FAT									

Table B. 57 Umfolozi surge arrester parameters for a fault at Normandie under 0.7pf loading conditions

Parameter		Units	PSB	ABB		Siemens			Areva	
Maximum continuous overvoltage, $MCOV$		kV	49.7006	72		58			58	
Rated voltage, U_r		kV	62.1258	90		72			72	
Residual voltage, U_{res}		kV	*	***	***	184,184	206,206	169,173	196	215
discharge current, I_d		A	0.0000	***	***	***			***	***
Nominal discharge current, I_n		kA	*	10	20	10	20	10	10	20
Energy absorption capability, EAC		kJ/kV	0	3.0,5.2,5.5,9.0	13.3,21.0	5,6	5,8	8,10	**	**
Classification			*****	1,2,3,	4,5	2,3	2,3	3,4	2	2
*	Not required									
**	Not specified									
***	by FAT									

Table B. 58 Bloedrivier surge arrester parameters for a fault at Normandie under 0.7pf loading conditions

Parameter		Units	PSB	ABB		Siemens			Areva	
Maximum continuous overvoltage, $MCOV$		kV	49.1977	72		58			58	
Rated voltage, U_r		kV	61.497	90		72			72	
Residual voltage, U_{res}		kV	*	***	***	184,184	206,206	169,173	196	215
discharge current, I_d		A	0.0000	***	***	***			***	***
Nominal discharge current, I_n		kA	*	10	20	10	20	10	10	20
Energy absorption capability, EAC		kJ/kV	0	3.0,5.2,5.5,9.0	13.3,21.0	5,6	5,8	8,10	**	**
Classification			*****	1,2,3,	4,5	2,3	2,3	3,4	2	2
*	Not required									
**	Not specified									
***	by FAT									

Table B. 59 Normandie surge arrester parameters for a fault at Normandie under 0.7pf loading conditions

Parameter		Units	PSB	ABB		Siemens			Areva	
Maximum continuous overvoltage, $MCOV$		kV	49.2924	72		58			58	
Rated voltage, U_r		kV	61.6155	90		72			72	
Residual voltage, U_{res}		kV	*	***	***	184,184	206,206	169,173	196	215
discharge current, I_d		A	0.0000	***	***	***			***	***
Nominal discharge current, I_n		kA	*	10	20	10	20	10	10	20
Energy absorption capability, EAC		kJ/kV	0	3.0,5.2,5.5,9.0	13.3,21.0	5,6	5,8	8,10	**	**
Classification			*****	1,2,3,	4,5	2,3	2,3	3,4	2	2
*	Not required									
**	Not specified									

Table B. 60 Empangeni surge arrester parameters for a fault at Normandie under 0.7pf loading conditions

Parameter		Units	MSPB	ABB		Siemens			Areva	
Maximum continuous overvoltage, $MCOV$		kV	49.7006	72		58			58	
Rated voltage, U_r		kV	62.1258	90		72			72	
Residual voltage, U_{res}		kV	*	***	***	184,184	206,206	169,173	196	215
discharge current, I_d		A	0.0000	***	***	***			***	***
Energy absorption capability, EAC		kJ/kV	0	3.0,5.2,5.5,9.0	13.3,21.0	5,6	5,8	8,10	**	**

Table B. 61 Umfolozi surge arrester parameters for a fault at Empangeni under 0.7pf loading conditions

Parameter	Units	PSB	ABB		Siemens			Areva	
Maximum continuous overvoltage, $MCOV$	kV	49.7006	72		58			58	
Rated voltage, U_r	kV	62.1258	90		72			72	
Residual voltage, U_{res}	kV	*	***	***	184,184	206,206	169,173	196	215
discharge current, I_d	A	0	***	***	***			***	***
Nominal discharge current, I_n	kA	*	10	20	10	20	10	10	20
Energy absorption capability, EAC	kJ/kV	0	3.0,5.2,5.5,9.0	13.3,21.0	5,6	5,8	8,10	**	**

Table B. 62 Bloedrivier surge arrester parameters for a fault at Empangeni under 0.7pf loading conditions

Parameter	Units	PSB	ABB		Siemens			Areva	
Maximum continuous overvoltage, $MCOV$	kV	49.2006	72		58			58	
Rated voltage, U_r	kV	61.5008	90		72			72	
Residual voltage, U_{res}	kV	*	***	***	184,184	206,206	169,173	196	215
discharge current, I_d	A	0	***	***	***			***	***
Nominal discharge current, I_n	kA	*	10	20	10	20	10	10	20
Energy absorption capability, EAC	kJ/kV	0	3.0,5.2,5.5,9.0	13.3,21.0	5,6	5,8	8,10	**	**

Table B. 63 Normandie surge arrester parameters for a fault at Empangeni under 0.7pf loading conditions

Parameter	Units	PSB	ABB	Siemens				Areva	
Maximum continuous overvoltage, $MCOV$	kV	49.2919	72	58				58	
Rated voltage, U_r	kV	61.6149	90	72				72	
Residual voltage, U_{res}	kV	*	***	***	184,184	206,206	169,173	196	215
discharge current, I_d	A	0	***	***	***			***	***
Nominal discharge current, I_n	kA	*	10	20	10	20	10	10	20
Energy absorption capability, EAC	kJ/kV	0	3.0,5.2,5.5,9.0	13.3,21.0	5,6	5,8	8,10	**	**
Classification		*****	1,2,3,	4,5	2,3	2,3	3,4	2	2
*	Not required								
**	Not specified								
***	by FAT								

Table B. 64 Empangeni surge arrester parameters for a fault at Empangeni under 0.7pf loading conditions

Parameter	Units	PSB	ABB	Siemens				Areva	
Maximum continuous overvoltage, $MCOV$	kV	49.7006	72	58				58	
Rated voltage, U_r	kV	62.1258	90	72				72	
Residual voltage, U_{res}	kV	*	***	***	184,184	206,206	169,173	196	215
discharge current, I_d	A	0	***	***	***			***	***
Nominal discharge current, I_n	kA	*	10	20	10	20	10	10	20
Energy absorption capability, EAC	kJ/kV	0	3.0,5.2,5.5,9.0	13.3,21.0	5,6	5,8	8,10	**	**
Classification		*****	1,2,3,	4,5	2,3	2,3	3,4	2	2
*	Not required								
**	Not specified								
***	by FAT								

Table B. 65 U_c parameters during a fault at Umfolozi under $1pf$ loading conditions

	PSB	PSAT	Difference (%)
Bus #	Uc (kV)		
1	49.65	52.71	6.1631
3	49.04	52.10	6.2398
5	49.05	52.24	6.5037
7	49.65	52.28	5.2971

Table B. 66 U_r parameters during a fault at Umfolozi under $1pf$ loading conditions

	PSAT	PSB	Difference (%)
Bus #	Ur (kV)		
1	65.8875	62.0625	-5.8054
3	65.1250	61.300	-5.8733
5	65.3000	61.3125	-6.1064
7	65.3500	62.0625	-5.0306

Table B. 67 U_c parameters during a fault at Bloedrivier under $1pf$ loading conditions

	PSB	PSAT	Difference (%)
Bus #	Uc (kV)		
1	49.6400	53.4300	7.6350
3	49.0400	54.0000	10.1142
5	49.0500	54.0000	10.0917
7	49.6400	52.0200	4.7945

Table B. 68 U_r parameters during a fault at Bloedrivier under $1pf$ loading conditions

	PSAT	PSB	Difference (%)
Bus #	Ur (kV)		
1	66.7875	62.0500	-7.0934
3	67.5000	61.3000	-9.1852
5	67.5625	61.3125	-9.2507
7	65.0250	62.0500	-4.5752

Table B. 69 U_c parameters during a fault at Normandie under $1pf$ loading conditions

	PSB	PSAT	Difference (%)
Bus #	Uc (kV)		
1	49.6500	53.4300	7.6133
3	49.0400	53.9500	10.0122
5	49.0500	54.0300	10.1529
7	49.6500	52.0200	4.7734

Table B. 70 U_r parameters during a fault at Normandie under $1pf$ loading conditions

	PSAT	PSB	Difference (%)
Bus #	Ur (kV)		
1	66.7875	62.0625	-7.0747
3	67.4375	61.3000	-9.1010
5	67.5375	61.3125	-9.2171
7	65.0250	62.0625	-4.5559

Table B. 71 U_c parameters during a fault at Empangeni under $1pf$ loading conditions

	PSB	PSAT	Difference (%)
Bus #	Uc (kV)		
1	49.65	53.97	8.7009
3	49.04	53.00	8.0750
5	49.05	53.09	8.2365
7	49.65	52.27	5.2769

Table B. 72 U_r parameters during a fault at Empangeni under $1pf$ loading conditions

	PSAT	PSB	Difference (%)
Bus #	Ur (kV)		
1	67.4625	63.5085	-5.8610
3	66.2500	63.5071	-4.1402
5	66.3625	63.5071	-4.3027
7	65.3375	62.1258	-4.9156

Table B. 73 U_c parameters during a fault at Umfolozi under $1pf$ loading conditions

	PSB	ATP	Difference (%)
Bus #	Uc (kV)		
1	49.65	50.8068	2.3299
3	49.04	50.8068	3.6028
5	49.05	50.8068	3.5817
7	49.65	49.6983	0.0973

Table B. 74 I_d parameters during a fault at Umfolozi under 1pf loading conditions

	ATP	PSB	Difference (%)
Bus #	I_d (A)		
1	0.8229	0.8667	5.3226
3	0.6670	0.6883	3.1934
5	2.2194	2.3711	6.8352
7	0.7883	0.8197	3.9833

Table B. 75 U_r parameters during a fault at Umfolozi under 1pf loading conditions

	PSB	ATP	Difference (%)
Bus #	U_r (kV)		
1	62.0625	63.5085	2.3299
3	61.3000	63.5085	3.6028
5	61.3125	63.5085	3.5817
7	62.0625	62.1229	0.0973

Table B. 76 EAC parameters during a fault at Umfolozi under 1pf loading conditions

	PSB	ATP	Difference (%)
Bus #	EAC (kJ/kV)		
1	1.8000	1.75000	2.8571
3	46.8000	45.8900	1.9830
5	12.3000	12.2700	0.2445
7	1.6000	1.54000	3.8961

Table B. 77 U_c parameters during a fault at Bloedrivier under 1pf loading conditions

	PSB	ATP	Difference (%)
Bus #	U_c (kV)		
1	49.6400	50.8068	2.3505
3	49.0400	50.8045	3.5981
5	49.0500	50.8045	3.5770
7	49.6400	49.6989	0.1187

Table B. 78 I_d parameters during a fault at Bloedrivier under 1pf loading conditions

	ATP	PSB	Difference (%)
Bus #	I_d (A)		
1	0.8667	0.8635	0.3706
3	0.6883	0.6871	0.1746
5	2.3711	2.3177	2.3040
7	0.8197	0.8667	-5.4229

Table B. 79 U_r parameters during a fault at Bloedrivier under $1pf$ loading conditions

	PSB	ATP	Difference (%)
Bus #	Ur (kV)		
1	62.0500	63.5085	2.3505
3	61.3000	63.5056	3.5981
5	61.3125	63.5056	3.5770
7	62.0500	62.1236	0.1187

Table B. 80 EAC parameters during a fault at Bloedrivier under $1pf$ loading conditions

	PSB	ATP	Difference (%)
Bus #	EAC (kJ/kV)		
1	0.0000	0.0000	0.0000
3	0.0000	0.0000	0.0000
5	0.0000	0.0000	0.0000
7	0.0000	0.0000	0.0000

Table B. 81 U_c parameters during a fault at Normandie under $1pf$ loading conditions

	PSB	ATP	Difference (%)
Bus #	Uc (kV)		
1	49.6500	50.8068	2.3299
3	49.0400	50.8068	3.6028
5	49.0500	50.8068	3.5817
7	49.6500	49.7006	0.1019

Table B. 82 I_d parameters during a fault at Normandie under $1pf$ loading conditions

	ATP	PSB	Difference (%)
Bus #	I _d (A)		
1	0.8654	0.8600	0.6279
3	0.6883	0.6845	0.5551
5	2.3711	2.3620	0.3853
7	0.8194	0.8154	0.4906

Table B. 83 U_r parameters during a fault at Normandie under $1pf$ loading conditions

	PSB	ATP	Difference (%)
Bus #	Ur (kV)		
1	62.0625	63.5085	2.3299
3	61.3000	63.5085	3.6028
5	61.3125	63.5085	3.5817
7	62.0625	62.1258	0.1019

Table B. 84 EAC parameters during a fault at Normandie under $1pf$ loading conditions

	PSB	ATP	Difference (%)
Bus #	EAC (kJ/kV)		
1	2.1000	2.2000	4.7619
3	0.4000	0.3800	-5.0000
5	0.0000	0.0001	0.0000
7	1.9000	1.8750	-1.3158

Table B. 85 U_c parameters during a fault at Empangeni under $1pf$ loading conditions

	PSB	ATP	Difference (%)
Bus #	Uc (kV)		
1	49.65	50.8068	2.3299
3	49.04	50.8057	3.6005
5	49.05	50.8057	3.5794
7	49.65	49.7006	0.1019

Table B. 86 I_d parameters during a fault at Empangeni under $1pf$ loading conditions

	ATP	PSB	Difference (%)
Bus #	I _d (A)		
1	0.8790	0.8654	1.5715
3	0.6398	0.6883	7.0463
5	2.3740	2.371	-0.1265
7	0.8951	0.8194	-9.2385

Table B. 87 U_r parameters during a fault at Empangeni under 1pf loading conditions

	PSB	ATP	Difference (%)
Bus #	U _r (kV)		
1	62.06250	63.5085	2.3299
3	61.30000	63.50713	3.6005
5	61.31250	63.50713	3.5794
7	62.06250	62.12575	0.1019

Table B. 88 EAC parameters during a fault at Empangeni under 1pf loading conditions

	PSB	ATP	Difference (%)
Bus #	EAC (kJ/kV)		
1	0.2000	0.19000	-5.0000
3	0.1000	0.09700	-3.0000
5	1.9000	1.87000	-1.6043
7	8.6000	8.54000	-0.6977

Table B. 89 U_c parameters during a fault at Umfolozi under 1pf loading conditions

	PSAT	ATP	Difference (%)
Bus #	U _c (kV)		
1	52.7100	50.8068	-3.6107
3	52.1000	50.8068	-2.4821
5	52.2400	50.8068	-2.7435
7	52.2800	49.6983	-4.9382

Table B. 90 U_r parameters during a fault at Umfolozi under 1pf loading conditions

	PSAT	ATP	Difference (%)
Bus #	U _r (kV)		
1	65.8875	63.5085	-3.6107
3	65.1250	63.5085	-2.4821
5	65.3000	63.5085	-2.7435
7	65.3500	62.12288	-4.9382

Table B. 91 U_c parameters during a fault at Bloedrivier under $1pf$ loading conditions

	PSAT	ATP	Difference (%)
Bus #	Uc (kV)		
1	53.4300	50.8068	-4.9096
3	54.0000	50.8045	-5.9176
5	54.0500	50.8045	-6.0046
7	52.0200	49.6989	-4.4619

Table B. 92 U_r parameters during a fault at Bloedrivier under $1pf$ loading conditions

	PSAT	ATP	Difference (%)
Bus #	U _r (kV)		
1	66.7875	63.5085	-4.9096
3	67.5000	63.5056	-5.9176
5	67.5625	63.5056	-6.0046
7	65.0250	62.1236	-4.4619

Table B. 93 U_c parameters during a fault at Normandie under $1pf$ loading conditions

	PSAT	ATP	Difference (%)
Bus #	U _c (kV)		
1	53.4300	50.8068	-4.9096
3	53.9500	50.8068	-5.8261
5	54.0300	50.8068	-5.9656
7	52.0200	49.7006	-4.4587

Table B. 94 U_r parameters during a fault at Normandie under $1pf$ loading conditions

	PSAT	ATP	Difference (%)
Bus #	U _r (kV)		
1	66.7875	63.5085	-4.9096
3	67.4375	63.5085	-5.8261
5	67.5375	63.5085	-5.9656
7	65.0250	62.1258	-4.4587

Table B. 95 U_c parameters during a fault at Empangeni under 1pf loading conditions

	PSAT	ATP	Difference (%)
Bus #	Uc (kV)		
1	53.9700	50.8068	-5.8610
3	53.0000	50.8057	-4.1402
5	53.0900	50.8057	-4.3027
7	52.2700	49.7006	-4.9156

Table B. 96 U_r parameters during a fault at Empangeni under 1pf loading conditions

	PSAT	ATP	Difference (%)
Bus #	U _r (kV)		
1	67.4625	63.5085	-5.8610
3	66.2500	63.50713	-4.1402
5	66.3625	63.50713	-4.3027
7	65.3375	62.12575	-4.9156

Appendix C

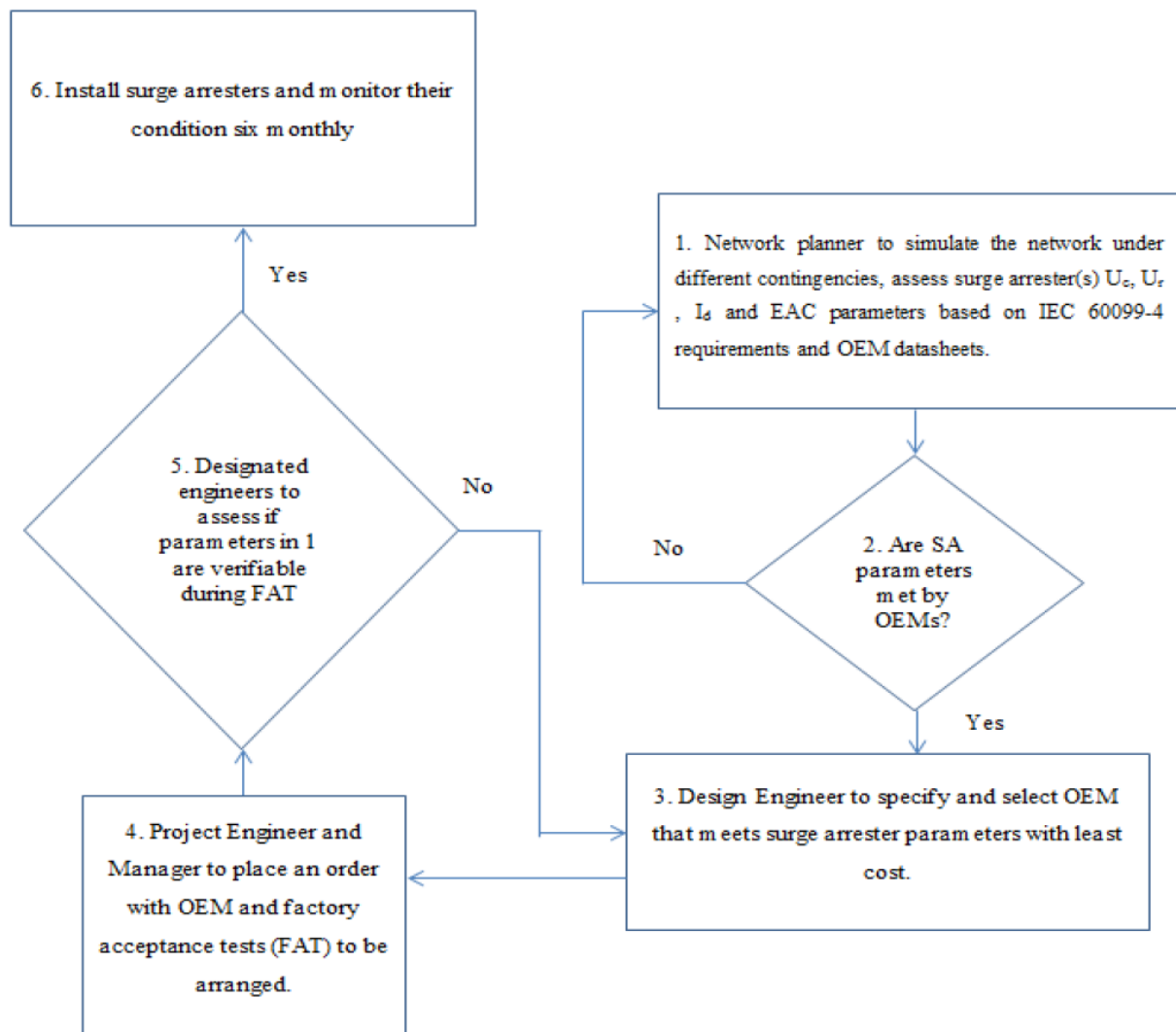


Figure C. 1 Guideline for surge arrester selection process in traction network applications

Table C. 1 Transnet's tariff information used in the cost-benefit evaluation in this study

Transflex 1 tariff

Non-local authority

		Active energy charge [c/kWh]												Network capacity charge [R/POD/day]	
Transmission zone	Voltage	High demand season [Jun - Aug]						Low demand season [Sep - May]							
		Peak	Standard	Off Peak	Peak	Standard	Off Peak	Peak	Standard	Off Peak					
		VAT incl	VAT incl	VAT incl	VAT incl	VAT incl	VAT incl	VAT incl	VAT incl	VAT incl	VAT incl	VAT incl	VAT incl		
≤ 300km	< 500V	272,34	310,47	82,86	94,46	45,24	51,57	89,18	101,67	61,54	70,16	39,23	44,72	R 4 485,19	R 5 113,12
	≥ 500V & < 66kV	268,06	305,59	81,21	92,58	44,10	50,27	87,44	99,68	60,19	68,62	38,18	43,53	R 4 110,32	R 4 685,76
	≥ 66kV & ≤ 132kV	259,58	295,92	78,63	89,64	42,71	48,69	84,69	96,55	58,28	66,44	36,98	42,16	R 3 983,82	R 4 541,55
	> 132kV*	244,65	278,90	74,11	84,49	40,25	45,89	79,82	90,99	54,92	62,61	34,85	39,73	R 3 588,14	R 4 090,48
> 300km and ≤ 600km	< 500V	275,01	313,51	83,63	95,34	45,62	52,01	90,03	102,63	62,10	70,79	39,57	45,11	R 4 530,06	R 5 164,27
	≥ 500V & < 66kV	270,68	308,58	81,96	93,43	44,48	50,71	88,27	100,63	60,73	69,23	38,50	43,89	R 4 151,40	R 4 732,60
	≥ 66kV & ≤ 132kV	262,09	298,78	79,37	90,48	43,07	49,10	85,47	97,44	58,79	67,02	37,28	42,50	R 4 023,61	R 4 586,92
	> 132kV*	247,05	281,64	74,82	85,29	40,60	46,28	80,55	91,83	55,43	63,19	35,15	40,07	R 3 624,04	R 4 131,41
> 600km and ≤ 900km	< 500V	277,71	316,59	84,40	96,22	46,01	52,45	90,86	103,58	62,65	71,42	39,91	45,50	R 4 574,89	R 5 215,37
	≥ 500V & < 66kV	273,35	311,62	82,74	94,32	44,89	51,17	89,10	101,57	61,27	69,85	38,84	44,28	R 4 192,48	R 4 779,43
	≥ 66kV & ≤ 132kV	264,70	301,76	80,12	91,34	43,44	49,52	86,27	98,35	59,35	67,66	37,61	42,88	R 4 063,46	R 4 632,34
	> 132kV*	249,48	284,41	75,51	86,08	40,97	46,71	81,33	92,72	55,94	63,77	35,46	40,42	R 3 659,89	R 4 172,27
> 900km	< 500V	280,41	319,67	85,20	97,13	46,42	52,92	91,71	104,55	63,22	72,07	40,24	45,87	R 4 619,74	R 5 268,50
	≥ 500V & < 66kV	276,02	314,66	83,52	95,21	45,27	51,61	89,94	102,53	61,84	70,50	39,17	44,65	R 4 233,58	R 4 826,28
	≥ 66kV & ≤ 132kV	267,30	304,72	80,86	92,18	43,84	49,98	87,07	99,26	59,89	68,27	37,95	43,26	R 4 103,31	R 4 677,77
	> 132kV*	252,02	287,30	76,38	87,07	41,50	47,31	82,26	93,78	56,63	64,56	35,95	40,98	R 3 695,78	R 4 213,19

* 132 kV or Transmission connected

Customer categories	Service charge [R/account/day]	Administration charge [R/POD/day]
	VAT incl	VAT incl
> 1 MVA	R 177,75 R 202,64	R 80,11 R 91,33
Key customers	R 3 483,16 R 3 970,80	R 111,24 R 126,81

Voltage	Ancillary service charge [c/kWh]
	VAT incl
< 500V	0,36 0,41
≥ 500V & < 66kV	0,35 0,40
≥ 66kV & ≤ 132kV	0,33 0,38
> 132kV*	0,31 0,35

* 132 kV or Transmission connected

Electrification and rural network subsidy charge [c/kWh]	Affordability subsidy charge [c/kWh] payable by non-local authority tariffs
VAT incl	VAT incl
6.93 7.90	2.65 3.02

Reactive energy charge [c/kVArh]			
High season		Low season	
VAT incl		VAT incl	
8.28 9.44		8.28 9.44	

Table C. 2 Financial evaluation of the EGTN's 88kV surge arrester replacement project

88kV surge arresters for replacement					Investment (2018 Rands)	R 2 943 615	
Substation	Location	QTY	Unit cost (2015 R)	SA Total Cost	Year	Cash flow	Present value
Umfolozi	Empangeni 88kV line bay	6	R 13 526	R 97 390.08	0	-R 2 943 615	-R 2 943 615
	Bloedrivier 88kV line bay	3	R 13 526	R 48 695.04	1	R 294 362	R 323 798
	Transformer 1 bay	3	R 13 526	R 48 695.04	2	R 323 798	R 391 795
	Transformer 1 bay	3	R 13 526	R 48 695.04	3	R 356 177	R 474 072
Bloedrivier	Normandie 88kV line bay	3	R 13 526	R 48 695.04	4	R 391 795	R 573 627
	Umfolozi 88kV line bay	3	R 13 526	R 48 695.04	5	R 430 975	R 694 089
	Transformer 275/88kV 1 bay	3	R 13 526	R 48 695.04	6	R 474 072	R 839 848
	Transformer 275/88kV 2 bay	3	R 13 526	R 48 695.04	7	R 521 479	R 1 016 216
	Transformer 88/22kV 12 bay	3	R 13 526	R 48 695.04	8	R 573 627	R 1 229 621
Normandie	Bloedrivier 88kV line bay	3	R 13 526	R 48 695.04	9	R 630 990	R 1 487 842
	Transformer 275/88kV 11 bay	3	R 13 526	R 48 695.04	10	R 694 089	R 1 800 288
	Transformer 275/88kV 22 bay	3	R 13 526	R 48 695.04	11	R 763 498	R 2 178 349
Total Surge Arrester Costs				R 633 035.52	12	R 839 848	R 2 635 802
Engineering Costs (10% of total surge arrester costs)				R 696 339.07	13	R 923 833	R 3 189 320
Project Management Costs (15% of total surge arrester costs)				R 727 990.85	14	R 1 016 216	R 3 859 078
Labour Costs (40% of total surge arrester costs)				R 886 249.73	15	R 1 117 837	R 4 669 484
Total project costs				R 2 943 615.17	16	R 1 229 621	R 5 650 076
Notes: Normal surge arrester costs were received in 2015 and have been escalated by 10% for 2016 and 2017 financial years. Quotations from three different suppliers show that high energy rating surge arresters cost about 40% higher than normal surge arresters. Engineering costs include drawings, measurements and technical advice.					17	R 1 352 583	R 6 836 592
					18	R 1 487 842	R 8 272 276
					19	R 1 636 626	R 10 009 454
					20	R 1 800 288	R 12 111 439
					Net Present Value (NPV)		R 65 299 450
					Internal rate of return, IRR (%)		10.9050

Appendix D

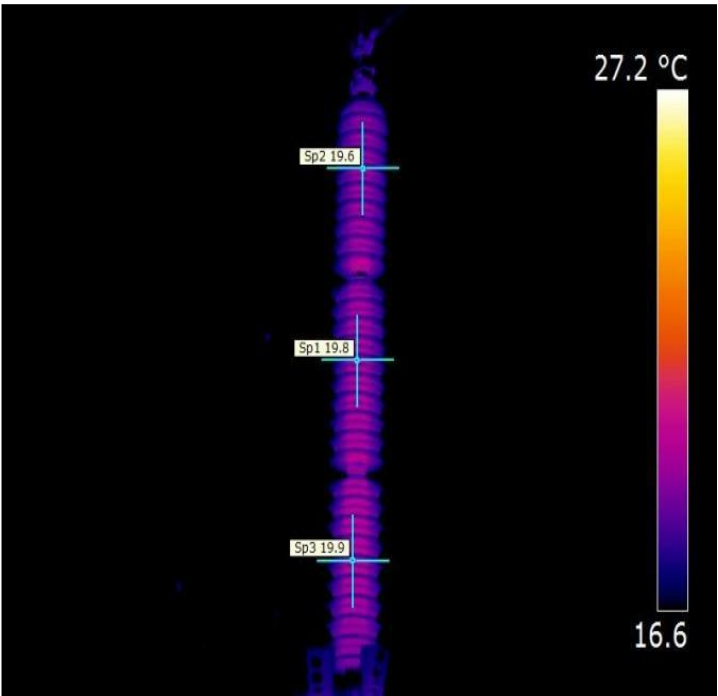


Figure D. 1 Thermal image of the Umfolozi – Empangeni red phase 88kV surge arrester

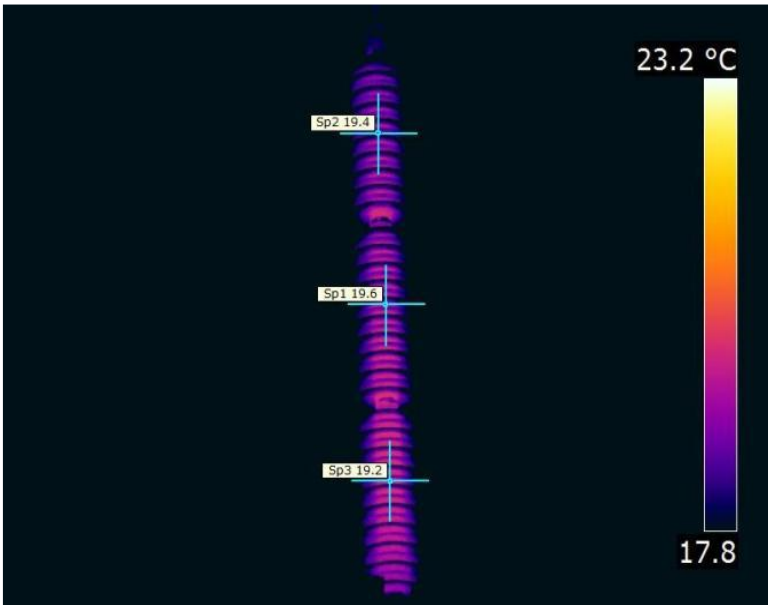


Figure D. 2 Thermal image of the Umfolozi – Empangeni white phase 88kV surge arrester

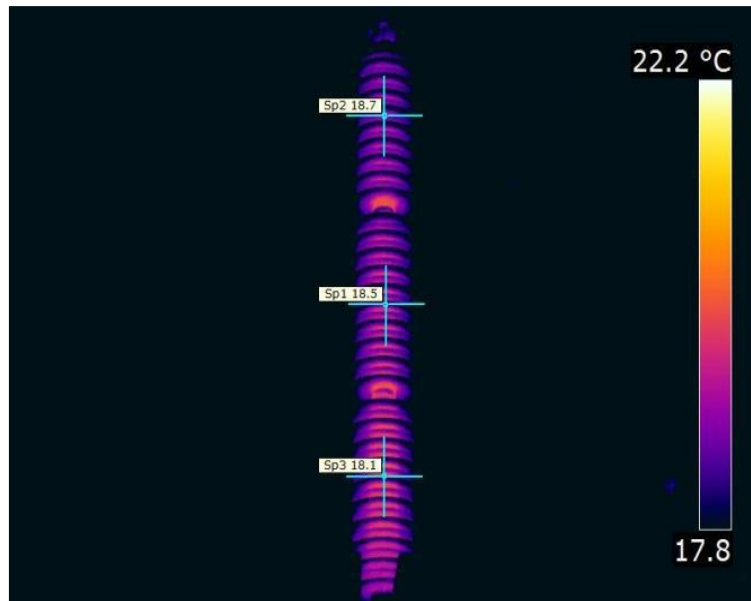


Figure D. 3 Thermal image of the Umfolozi – Empangeni blue phase 88kV surge arrester

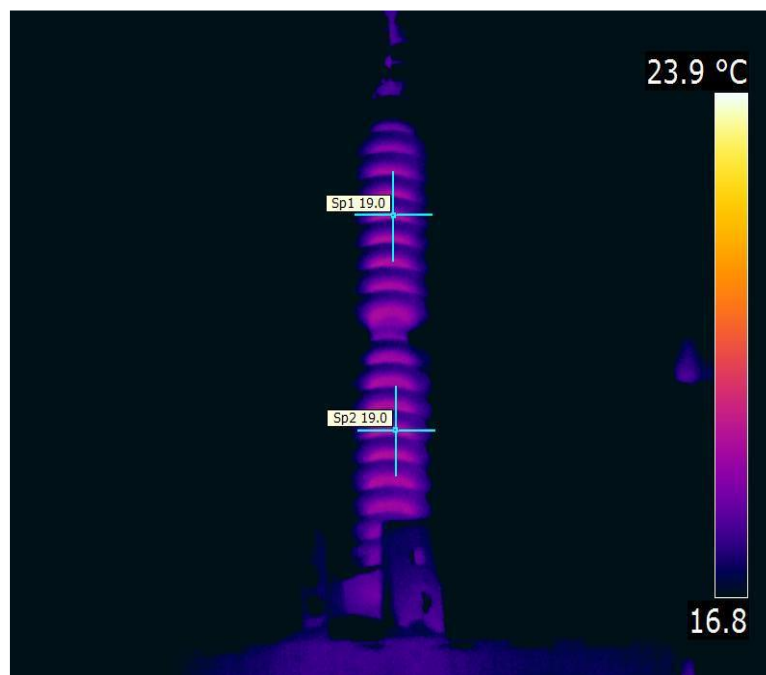


Figure D. 4 Thermal image of the Umfolozi – Bloedrivier red phase 88kV surge arrester



Figure D. 5 Thermal image of the Umfolozi – Bloedrivier white phase 88kV surge arrester

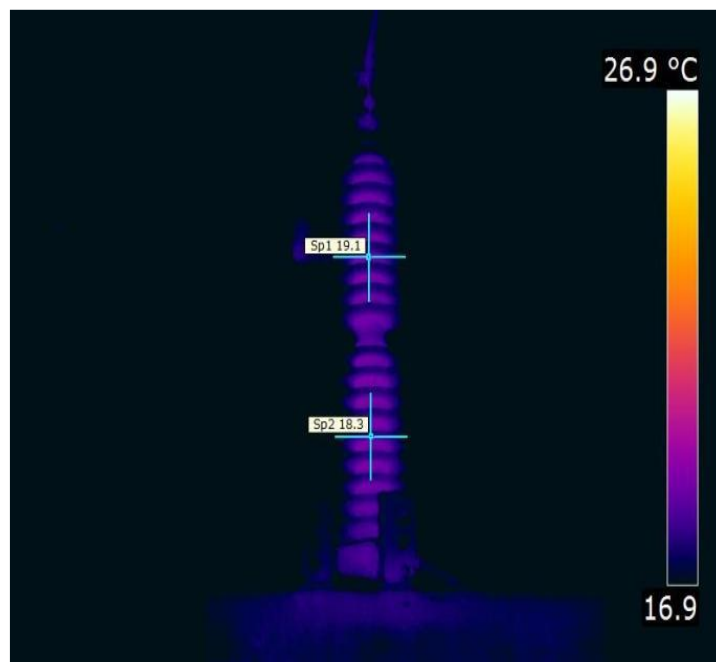


Figure D. 6 Thermal image of the Umfolozi – Bloedrivier blue phase 88kV surge arrester



Figure D. 7 Thermal image of the Bloedrivier - Normandie red phase 88kV surge arrester



Figure D. 8 Thermal image of the Bloedrivier - Normandie white phase 88kV surge arrester

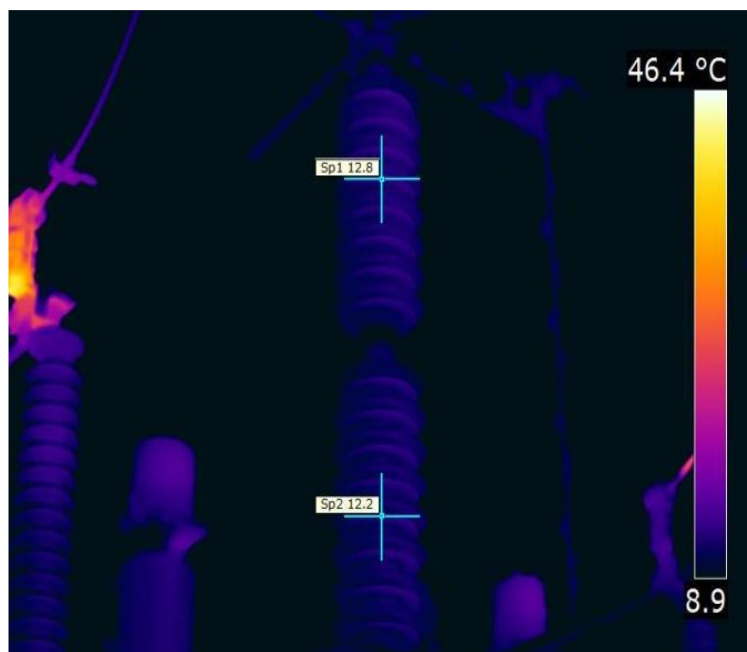


Figure D. 9 Thermal image of the Bloedrivier - Normandie blue phase 88kV surge arrester

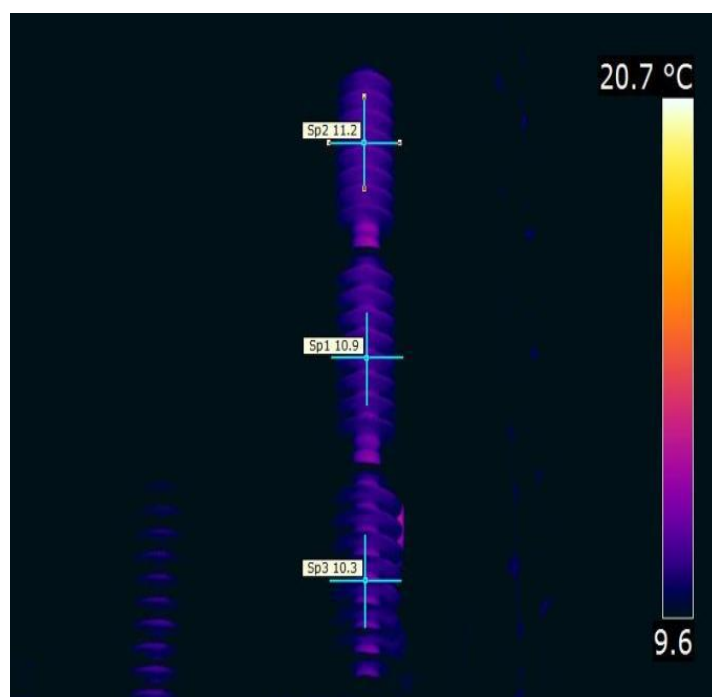


Figure D. 10 Thermal image of the Bloedrivier - Umfolozi red phase 88kV surge arrester

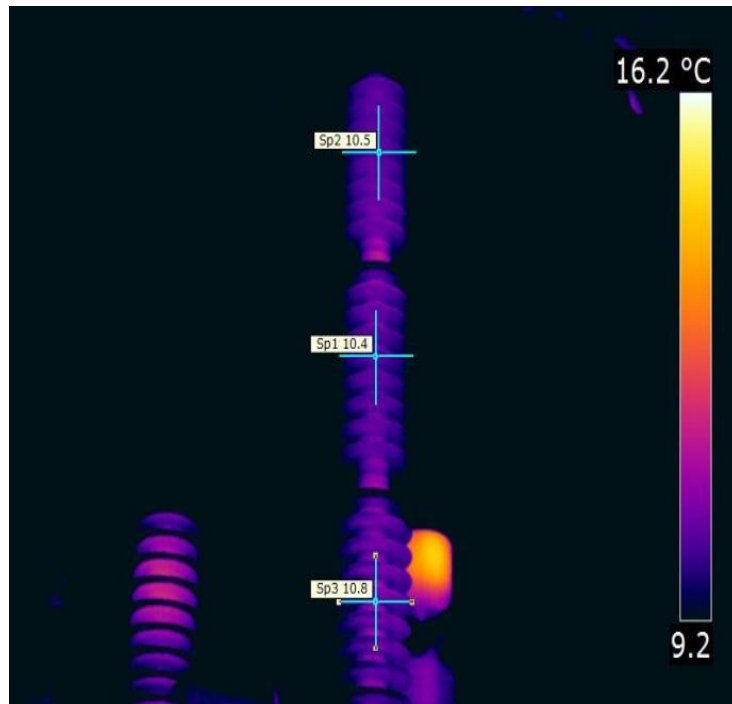


Figure D. 11 Thermal image of the Bloedrivier - Umfolozi white phase 88kV surge arrester

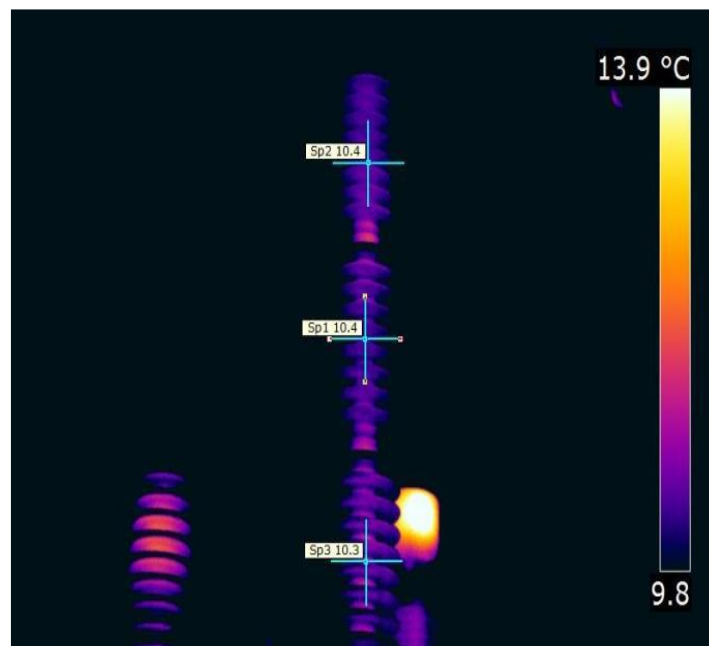


Figure D. 12 Thermal image of the Bloedrivier - Umfolozi blue phase 88kV surge arrester

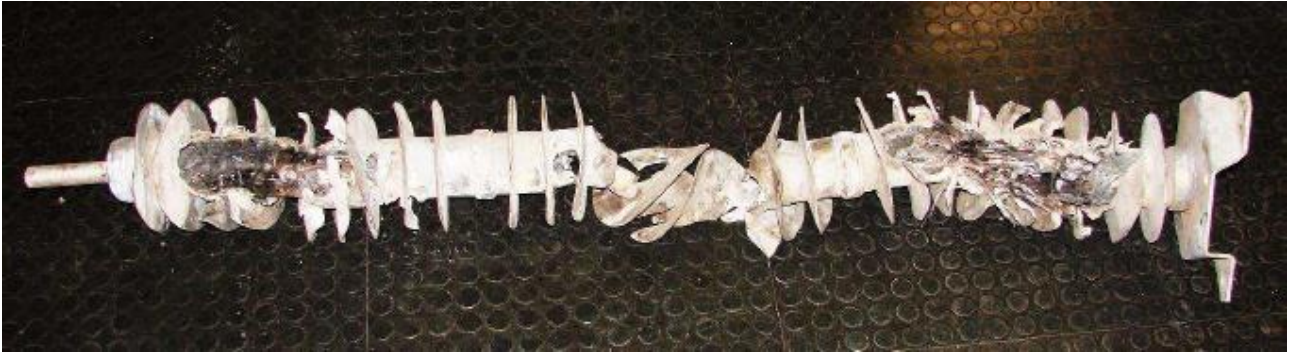


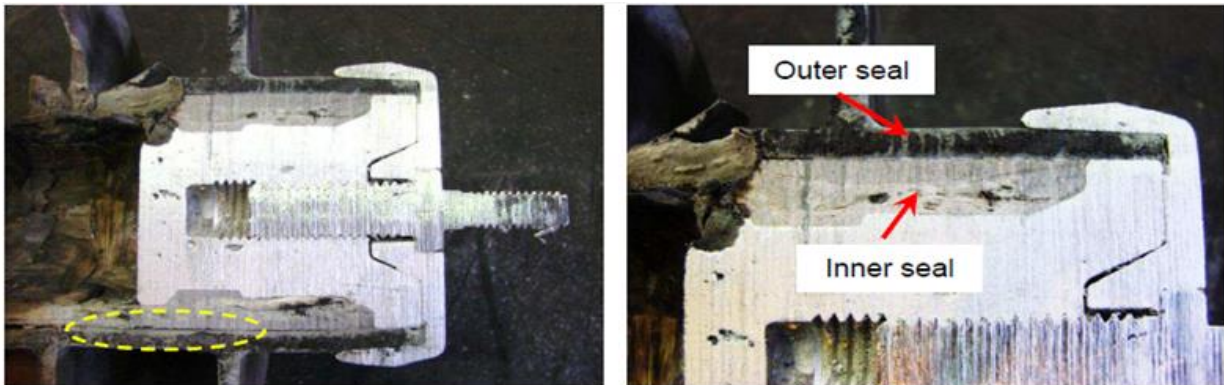
Figure D. 13 Faulted Umfolozi – Bloedrivier Areva surge arrester sent to RT&D unit before dissection [78]



(a)

(b)

Figure D. 14 Examination of the end caps for signs of corrosion in the Umfolozi-Bloedrivier 88kV surge arrester [78]



(a)

(b)

Figure D. 15 The dissection (a) of surge arrester end caps for signs of sealing failure (b) [78]